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University of California, San Diego
Institute of Geophysics and Planetary Physics

ANNUAL REPORT

Contract AF49(638)-1388

Geophysic Division
Air Force Office of Scientific Research
United States Air Force
Washington, D.C.

STUDY OF EARTH NOISE ON LAND AND SEA BOTTOM

Sponsored by Advanced Research Projects Agency
ARPA Order No. 202-63
ARPA Project Code No. 8652
Contract Starting Date: May 1, 1964
Contract Termination Date: April 30, 1967
Amount of Contract: \$1,186,344
Project Scientists: Hugh Bradner
Freeman Gilbert
Richard Haubrich
Walter Munk

(Phone: 714-453-2000)

(Also Incorporated - FINAL REPORT - Grant AFOSR-1007-66)

March 1, 1967

La Jolla, California 92038

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INSTITUTE OF GEOPHYSICS AND
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LA JOLLA LABORATORIES

POST OFFICE BOX 109
LA JOLLA, CALIFORNIA 92037

March 1, 1967

Air Force Office of Scientific Research
Attention: SRPG
Washington, D. C. 20550

Dear Sir:


Re: AFOSR Contract AF49(638)-1388
Annual Technical Summary Report:
Study of Earth Noise on Land and Sea Bottom
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This third annual report covers the period through the end of the thirty-fourth month of contract (to 1 March 1967). In addition, the contributions of Dr. Hugh Bradner and Dr. Carl L. Hubbs represent the final report for the AFOSR Equipment Grant, AFOSR-1007-66.

Sincerely,


Hugh Bradner


Richard Haubrich


Freeman Gilbert
Principal Investigator


Walter Munk

Distribution According to specified list for annual report.

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Part I

Dr. Gilbert's Section

GRAVITATIONALLY PERTURBED ELASTIC WAVES

FREEMAN GILBERT

INSTITUTE OF GEOPHYSICS AND PLANETARY PHYSICS

UNIVERSITY OF CALIFORNIA, SAN DIEGO

LA JOLLA, CALIFORNIA 92038

1 March 1967

ABSTRACT

In Lamb's problem there are two interface pulses. When the half space is incompressible the locked Rayleigh (\bar{S}) pulse travels with a speed $\gamma = 0.9553\beta$ where β is the shear pulse speed, and the leaking Rayleigh (\bar{P}) pulse travels with a speed $\delta = 1.966\beta$. In the absence of gravity the \bar{S} pulse is the more dominant pulse. The effect of gravity is to enhance the importance of the \bar{P} pulse. In the presence of gravity, as β decreases, the \bar{S} pulse becomes insignificant, and the \bar{P} pulse becomes dispersive and approaches the behavior of the classical gravity wave. Several theoretical seismograms and hodographs, for the buried line source problem, are presented to illustrate the effect of gravity.

The effect of gravity on dispersion curves, for a layer with a rigid bottom, is to distort them in such a way that one should observe wave groups similar to the classical gravity waves in a fluid layer when the shear speed is small. In addition one should observe very slow wave groups with wavelengths shortened by gravity. Several dispersion curves are presented to illustrate these features.

The propagator coefficient matrix is given for a transversely isotropic material including gravity.

GRAVITATIONALLY PERTURBED ELASTIC WAVES

Suppose a wave of amplitude A and wave number k propagates along the surface of an elastic half space of density ρ and rigidity μ . The wave motion extends to a depth of roughly k^{-1} . The strain is about kA so the shear strain energy per unit area is about $\mu(kA)^2 k^{-1}$, and the gravitational energy per unit area is about $\rho g A^2$. These energies are equal when $\rho g = \mu k$. Let $\epsilon = \rho g / \mu k = g / \beta^2 k$. When $\epsilon \gg 1$ the wave is predominantly a gravity wave. When $\epsilon \ll 1$ the wave is predominantly a shear wave.

Values of $\beta < 100$ m/sec are not uncommon in unconsolidated sediments. A wavelength of 6000m makes $\epsilon \sim 1$. Therefore it seems worthwhile to examine the effect of gravity on the propagation of elastic waves in "soft" media.

Bromwich (1898) considered the effect of gravity in Lamb's problem. The half space was considered to be incompressible. For waves of the form $\exp(ikx - i\omega t)$ Bromwich's secular function can be written (Ewing Jardetzky and Press, 1957)

$$S = (2\beta^2 k^2 - \omega^2)^2 - 4\beta^3 k^2 |k| (\beta^2 k^2 - \omega^2)^{1/2} - g\omega^2 |k| \quad (1)$$

Since S is even in k and ω it is sufficient to regard $k \geq 0$, $\omega \geq 0$. Furthermore, k will be restricted to be real, but ω will be regarded as complex. The right half ω plane has a branch cut from $\omega = \beta k$ to ∞ . Let $\omega = ck$, $\zeta = c^2 / \beta^2$, $\epsilon = g / \beta^2 k$. Then (1) becomes

$$S = \beta^4 k^4 [(2-\zeta)^2 - 4(1-\zeta)^{1/2} - \epsilon\zeta] = \beta^4 k^4 \sigma \quad (2)$$

The ζ plane has a branch cut from $\zeta=1$ to ∞ . When $\epsilon=0$ in (2) the three roots of σ are: one real root, ζ_+ , on the (+) sheet ($\text{Re}(1-\zeta)^{1/2} \geq 0$)

$$\zeta_+ = 0.91262197, \quad \epsilon=0 \quad (3)$$

and a conjugate pair of roots, ζ_- , on the (-) sheet ($\text{Re}(1-\zeta)^{1/2} \leq 0$)

$$\zeta_- = 3.5436890 \pm i2.2302850, \quad \epsilon=0 \quad (4)$$

The root on the (+) sheet represents the classical Rayleigh wave (locked \bar{S} pulse). The roots on the (-) sheet represent the second Rayleigh wave (leaking \bar{P} pulse). The \bar{S} pulse has a retrograde hodograph. Gilbert and Laster (1962) have shown that the \bar{P} pulse has a prograde hodograph. The fact that gravity waves have a prograde hodograph provides an indication of the rôle of gravity in Lamb's problem.

A graph of $\zeta_+(\epsilon)$ is presented in Fig. 1. As ϵ increases from 0, ζ_+ increases until $\zeta_+(1) = 1$. The root lies on the branch point. As ϵ increases from 1, ζ_+ passes through the branch point from the real axis of the (+) sheet to the real axis of the (-) sheet. For large ϵ

$$\zeta_+(\epsilon) = 8\epsilon^{-1} + O(\epsilon^{-2}), \quad (-) \text{ sheet} \quad (5)$$

The locus of $\zeta_-(\epsilon)$ in the first quadrant of the ζ plane is presented in Fig. 2. For large ϵ

$$\zeta_-(\epsilon) = \epsilon + O(1) \quad , \quad (-) \text{ sheet} \quad (6)$$

From (6) $c^2 \rightarrow gk^{-1}$ as $k \rightarrow 0$.

Thus when $k \ll g\beta^{-2}$ waves propagate as gravity waves. As k increases the gravity wave becomes shear coupled and develops into the leaking surface wave in Lamb's problem. Another wave, small when $k \ll g\beta^{-2}$ becomes more prominent as k increases. For $k > g\beta^{-2}$ this wave becomes the classical Rayleigh wave. The dimensionless (ω, κ) diagram is presented in Fig. 3. The waves are nearly nondispersive for $k\beta^2 g^{-1} > 0.1$.

Consider the buried line source problem for an incompressible half space including gravity. In dimensionless units, chosen so that shear waves arrive in unit time, the surface motion is $U(x, t)$ horizontally and $V(x, t)$ vertically for a source at depth h . The Laplace transforms of U and V for a unit step function source are

$$\bar{U} = -2 \operatorname{Im} \int_0^{i\infty} dp \frac{pn \exp(spx + isph)}{R(p) - i G s^{-1} p} \quad (7)$$

$$\bar{V} = \operatorname{Im} \int_0^{i\infty} dp \frac{(1-2p^2) \exp(spx + isph)}{R(p) - i G s^{-1} p}$$

where

$$R(p) = (1-2p^2)^2 - 4ip^3 n \quad ; \quad n = (1-p^2)^{1/2} \quad ; \quad \operatorname{Re} n \geq 0$$

$$G = gr/\beta^2$$

and r is the distance from source to receiver. Thus G is a somewhat inconvenient, although natural, dimensionless parameter to describe the effect of gravity.

The inversion of (7) can be made by standard methods

$$\begin{aligned} U(x,t) &= -2 \operatorname{Im} \left[\frac{\dot{p}p(t)\eta(t)}{R[p(t)]} + iG \int_0^t \frac{d\tau \dot{p}p^2(\tau)\eta(\tau)}{R^2[p(\tau)]} \exp\{iG(t-\tau)p(\tau)/R[p(\tau)]\} \right] \\ V(x,t) &= \operatorname{Im} \left[\frac{\dot{p}(1-2p^2(t))}{R[p(t)]} + iG \int_0^t \frac{d\tau \dot{p}p(\tau)(1-2p^2(\tau))}{R^2[p(\tau)]} \exp\{iG(t-\tau)p(\tau)/R[p(\tau)]\} \right] \end{aligned} \quad (8)$$

where

$$\dot{p} = -\sin\theta + i\cos\theta, \quad p(t) = \dot{p}t, \quad \tan\theta = x/h \quad (9)$$

In (8) the integrals can be evaluated for small G by expanding the exponential and integrating termwise. For large G the method of stationary phase can be used. Let $R = x/h$. For $R = 20$ (far from the epicenter) theoretical seismograms and hodographs for $0 \leq G \leq 20$ are presented in Fig. 4. The theoretical arrival time is 0.509 for the \bar{P} pulse and 1.047 for the \bar{S} pulse when $G = 0$. The hodographs are typical for interface pulses (Gilbert, Laster, Backus and Schell, 1962). As G increases the \bar{P} pulse arrives at increasingly earlier times relative to the \bar{S} pulse, and the \bar{P} orbit becomes more erect as it assumes the character of a dispersed gravity wave. The \bar{S} pulse decreases in size and becomes more dispersed as successive loops are added to its orbit for increasing G .

As another example of gravitationally perturbed elastic waves consider the dispersion of waves in a layer of thickness h with a rigid bottom and free top (Ewing, Jardetzky and Press, 1957). Gravity is included in the momentum equation and the layer is incompressible.

Let

$$W = \omega(hg^{-1})^{1/2}, \quad K = kh, \quad G = gh/\beta^2 \quad (10)$$

For selected values of G , $1 \leq G \leq 64$, dispersion curves are presented in Figs. 5-12. In the Figures labeled $g=0$ gravity has been excluded in the momentum equation. The curves labeled \sum_n are the dispersion curves. \sum_1 asymptotically approaches the Rayleigh phase velocity for large K . The curves for $n>1$ approach the shear phase velocity. The line labeled S is the shear phase velocity line. The curve labeled f is

$$W = (K \tanh K)^{1/2} = W_g \quad (11)$$

the dispersion curve for gravity waves in a fluid layer. It is included for reference.

When $W \approx W_g$ gravity is important. The major effects of gravity are: 1) to introduce additional regions of small group velocity and negative phase velocity; 2) to cause the \sum_n curves to approximate the f curve for $\epsilon < 1$; 3) to increase the magnitude of the phase velocity for all modes near the f curve.

For $K \neq 0$, $W > W_g$ for all modes because they are organ pipe modes. The motion is horizontal so there is no gravitational influence (Gilbert, 1964).

Of the three major effects perhaps the first two are more important for soft sediments. One should expect to observe very slow wavegroups with wavelengths shorter than commonly expected, and a wave group similar to the classical gravity wave in a fluid layer.

The propagator coefficient matrix, in the notation of Gilbert and Backus (1966), for P-SV waves in a transversely isotropic medium (Backus, 1967) including gravity is

$$A = \begin{bmatrix} 0 & k\lambda\beta^{-1} & \beta^{-1} & 0 \\ -k & 0 & 0 & \mu^{-1} \\ -\rho\omega^2 & \rho gk & 0 & k \\ \rho gk & -\rho\omega^2 + k^2(\lambda' + 2\mu' - \lambda^2\beta^{-1}) & -k\lambda\beta^{-1} & 0 \end{bmatrix} \quad (12)$$

where β in (12) is an elastic parameter, not the shear velocity.

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I am grateful to George Backus and Walter Munk for their interest and suggestions.

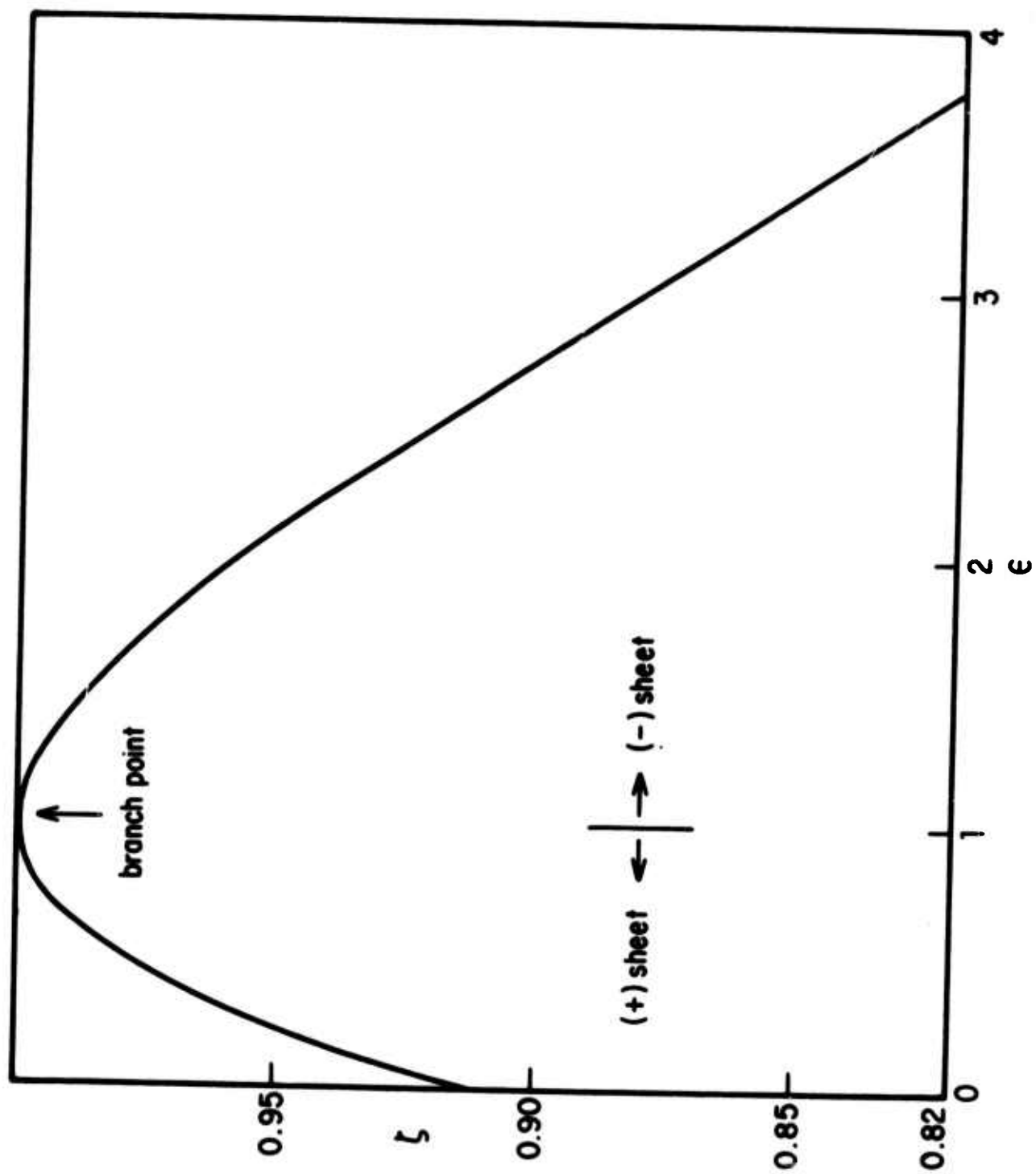
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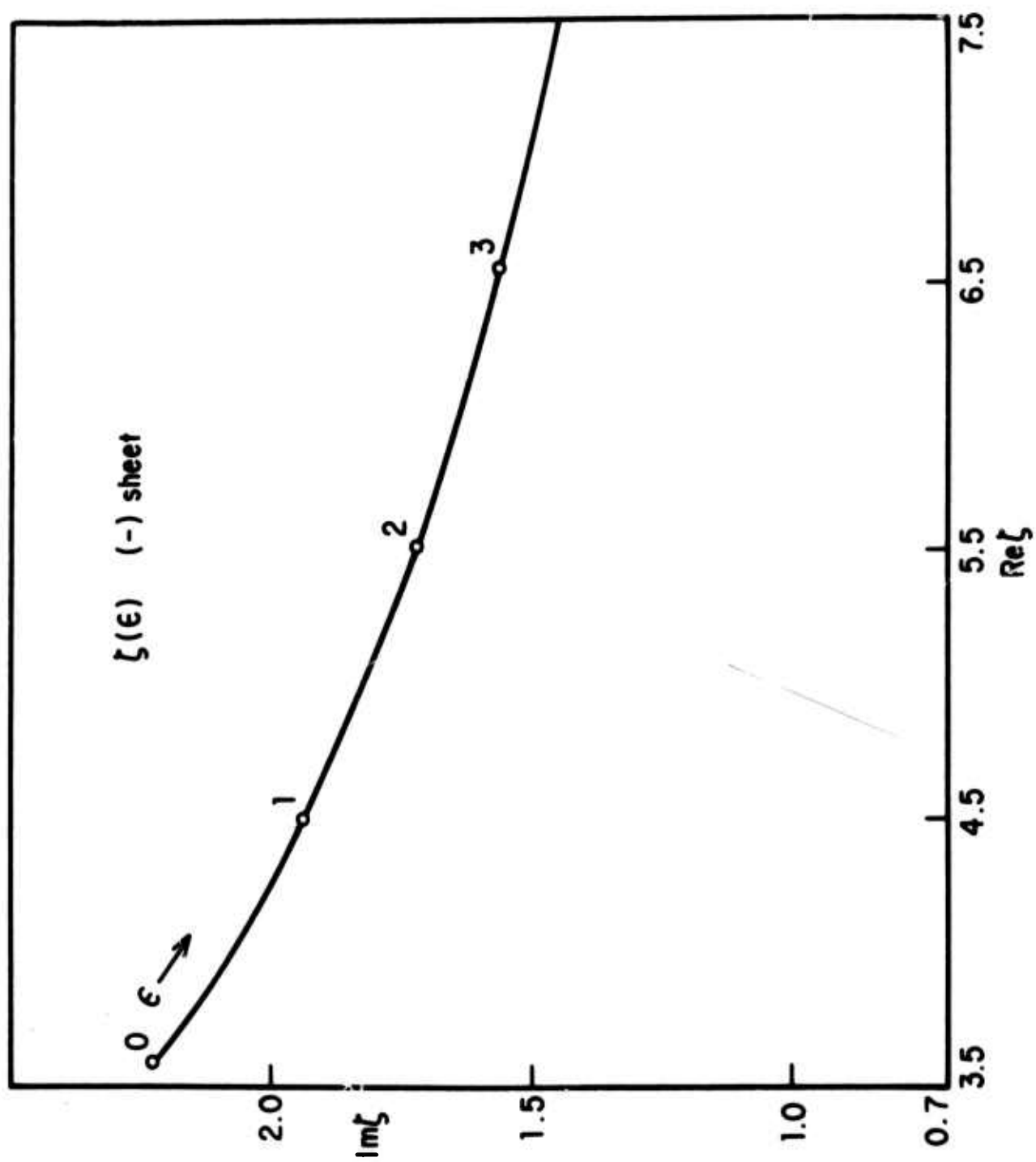
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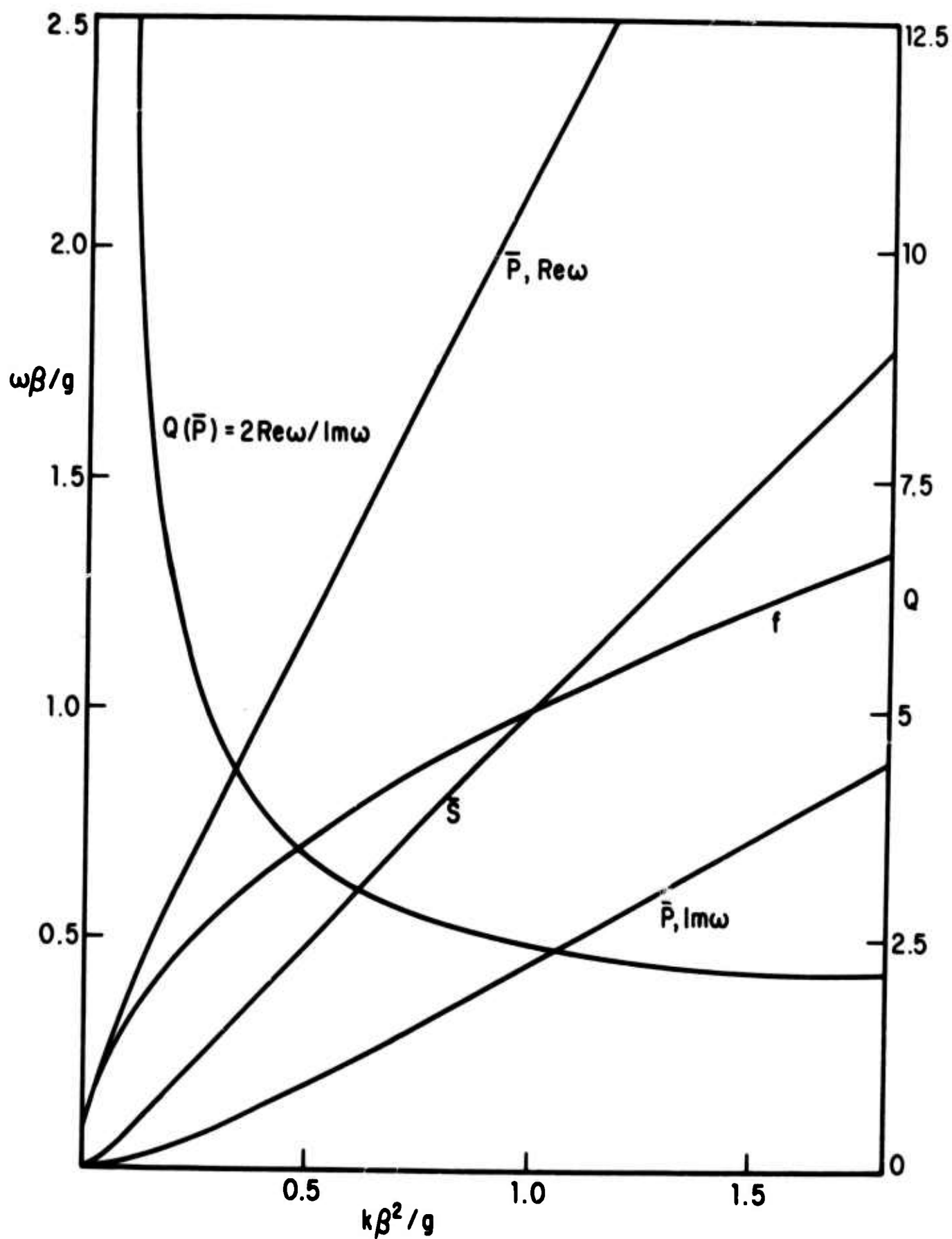
FIGURE CAPTIONS

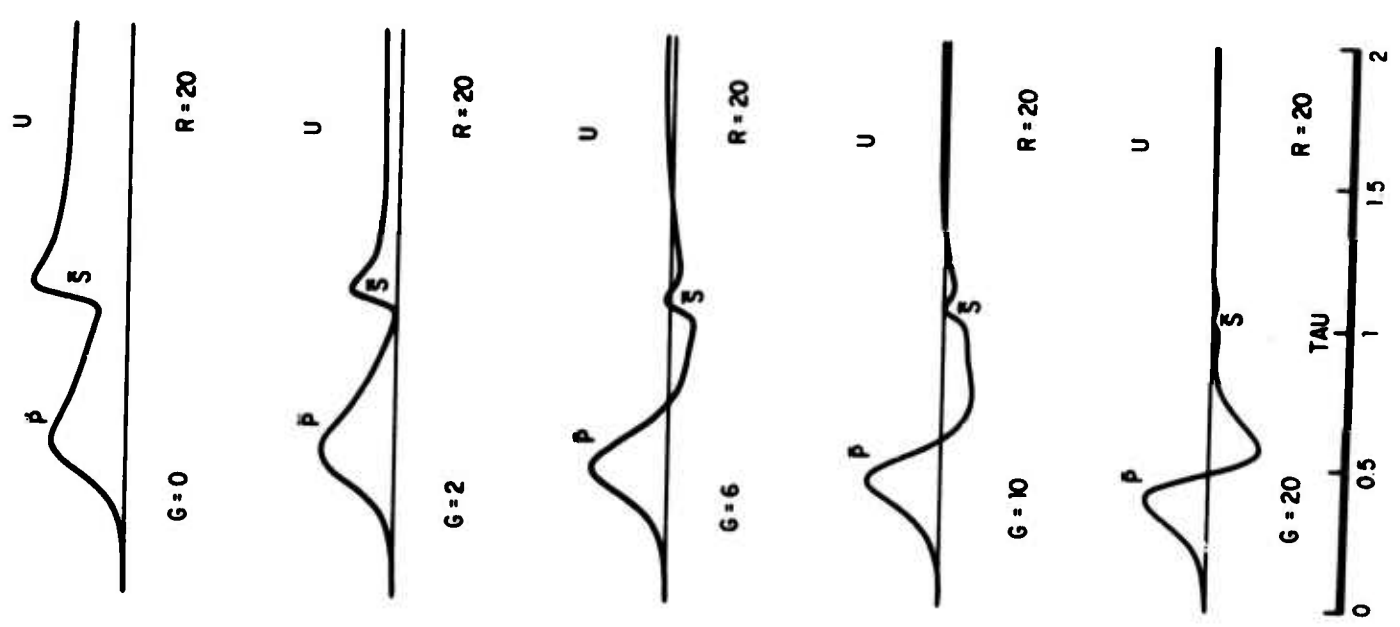
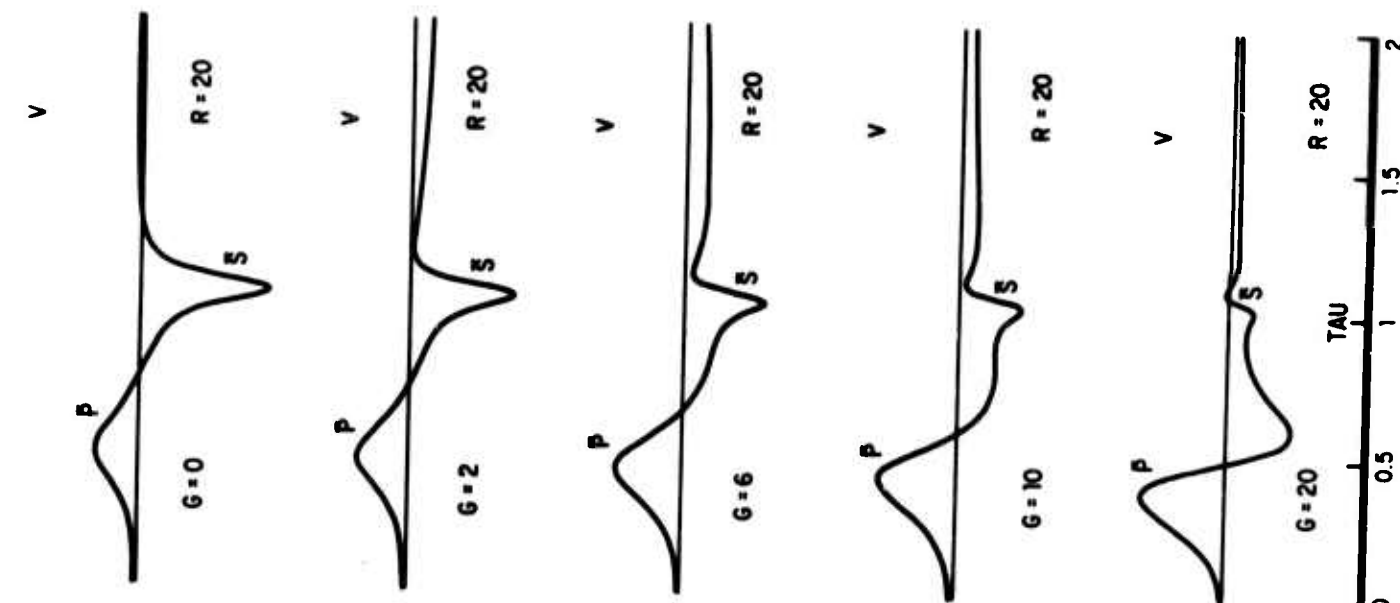
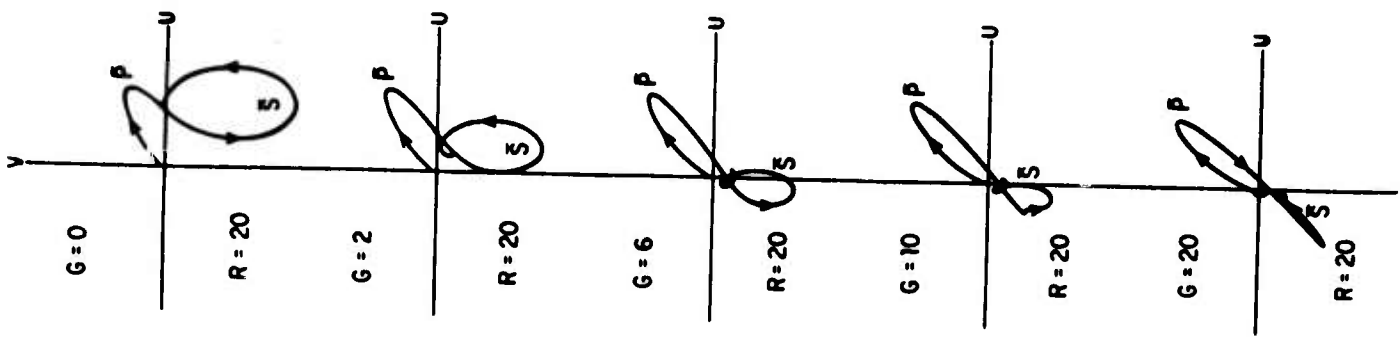
Figure

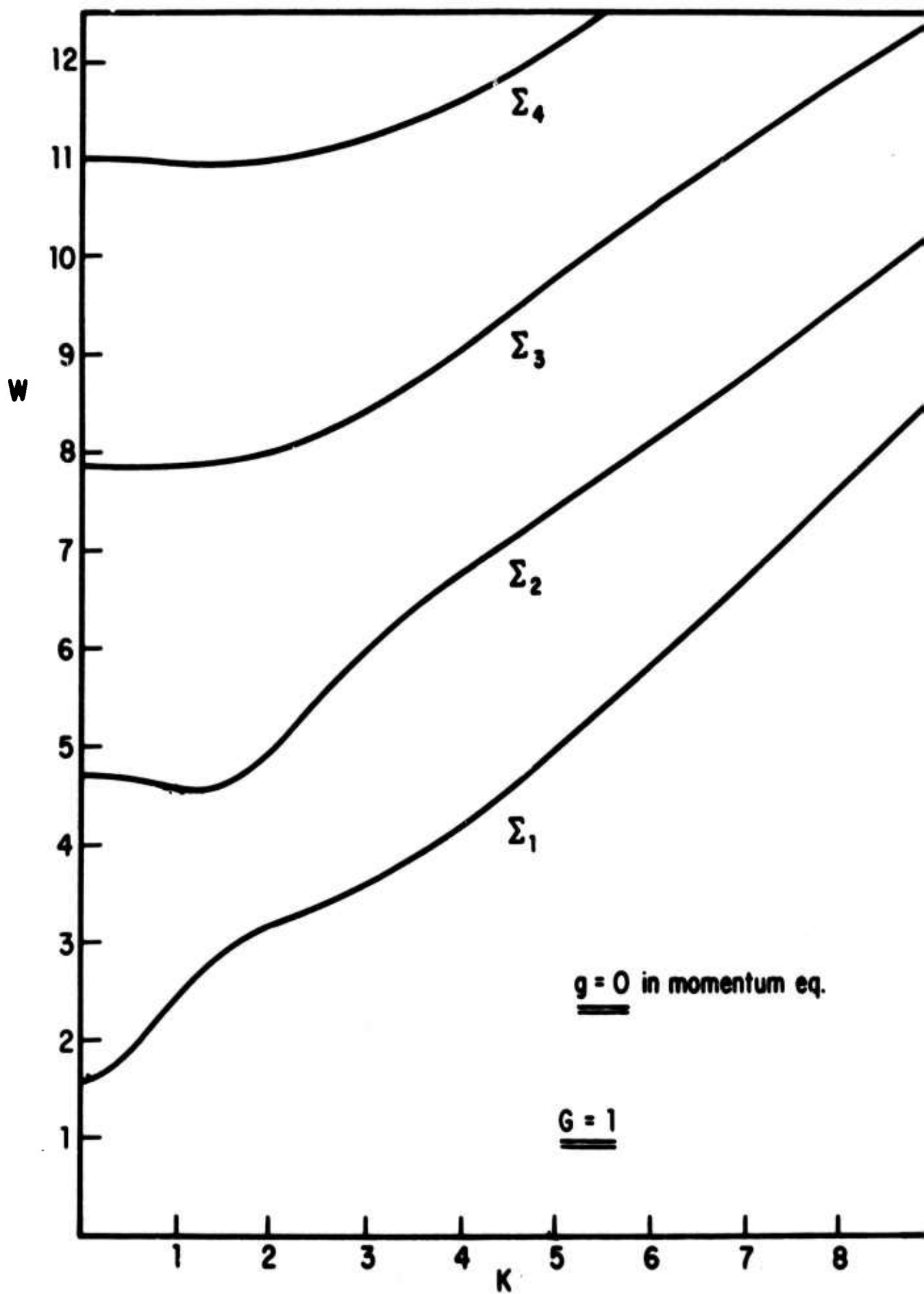
- 1 Migration of the root ζ_+ to the $(-)$ sheet.
2. Locus of ζ_- in the first quadrant.
3. Dispersion diagram for Lamb's problem. The curve labeled f is the dispersion curve for gravity waves. It is included for reference.
4. Seismograms and hodographs. $0 \leq G \leq 20$. $R=20$. The graphs labeled U represent horizontal motion and those labeled V represent vertical motion. The abscissa τ is $\beta t/r$.
5. Dispersion diagram. $G=1$. Gravity excluded.
6. Dispersion diagram. $G=1$. Gravity included
7. Dispersion diagram. $G=4$. Gravity excluded.
8. Dispersion diagram. $G=4$. Gravity included.
9. Dispersion diagram. $G=16$. Gravity excluded.
10. Dispersion diagram. $G=16$. Gravity included.
11. Dispersion diagram. $G=16$. Gravity included.
12. Dispersion diagram. $G=64$. Gravity included.

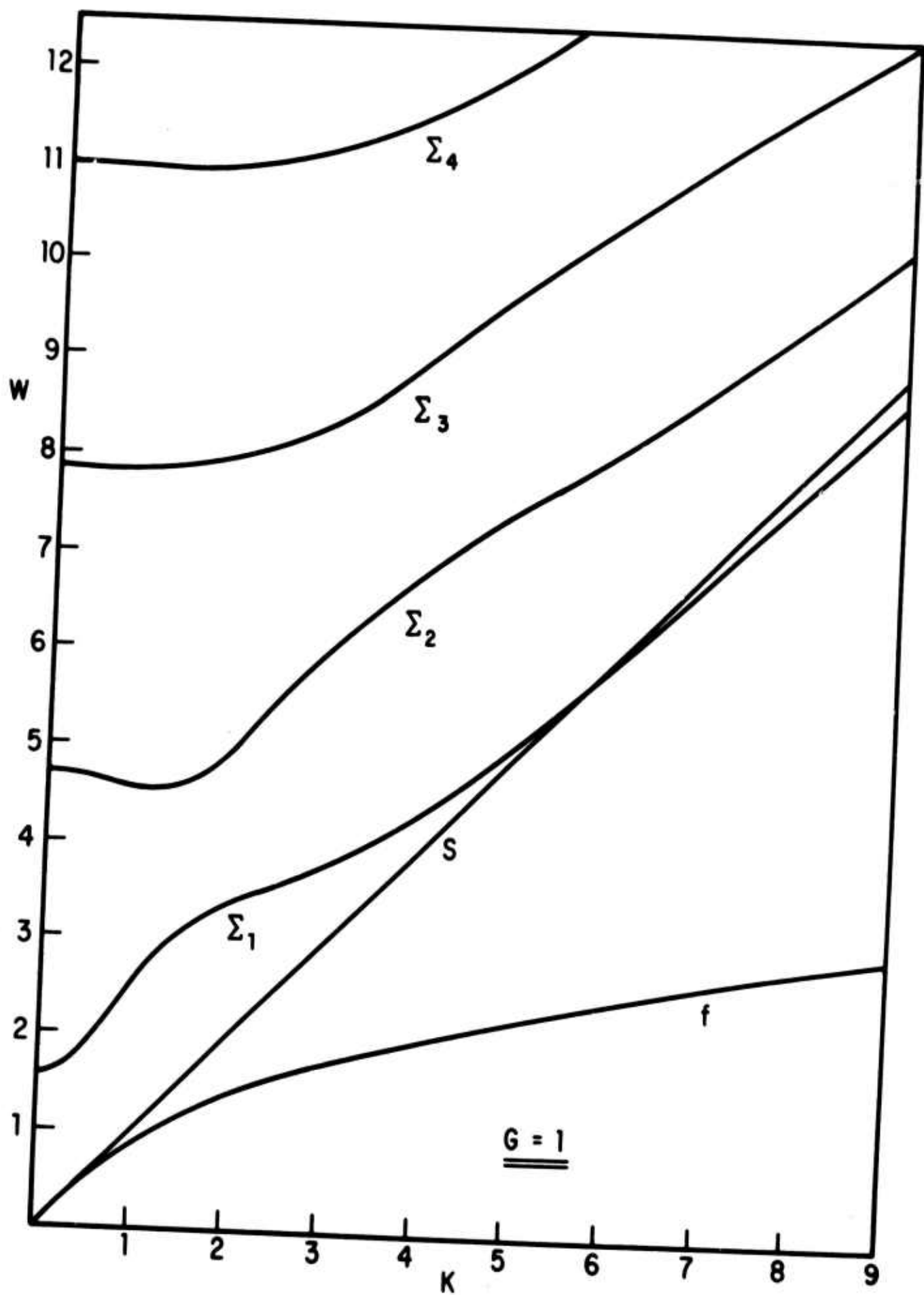


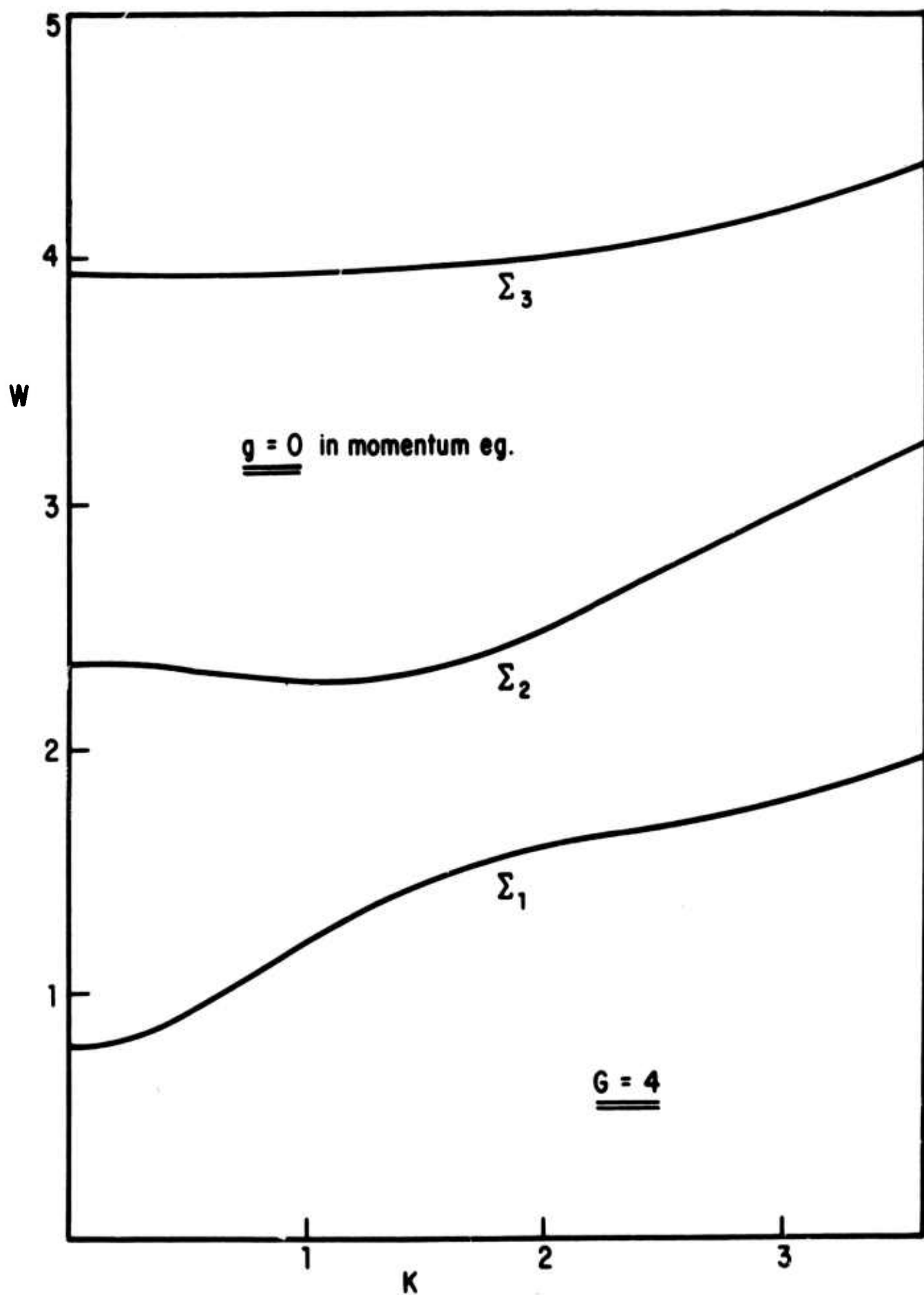


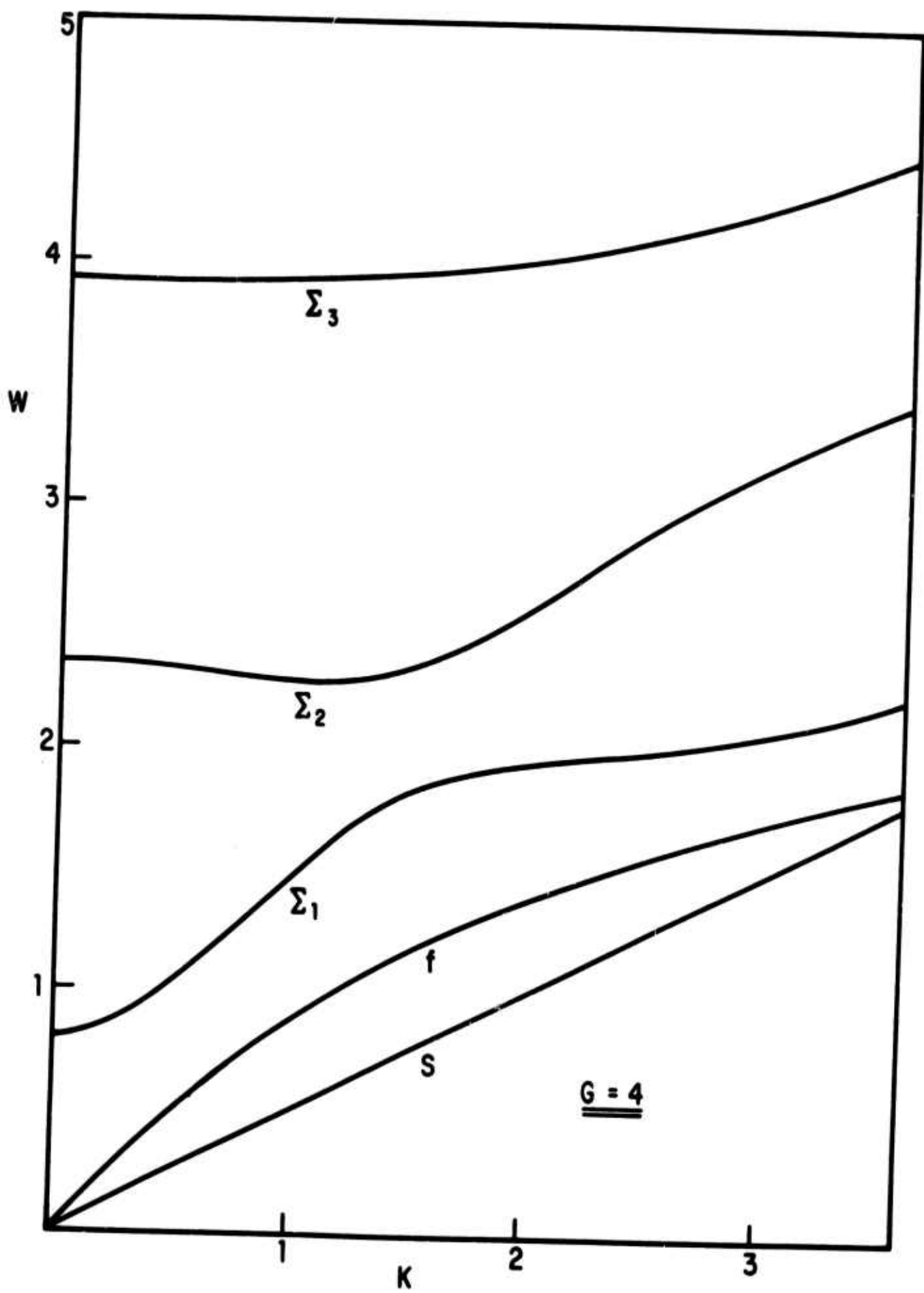


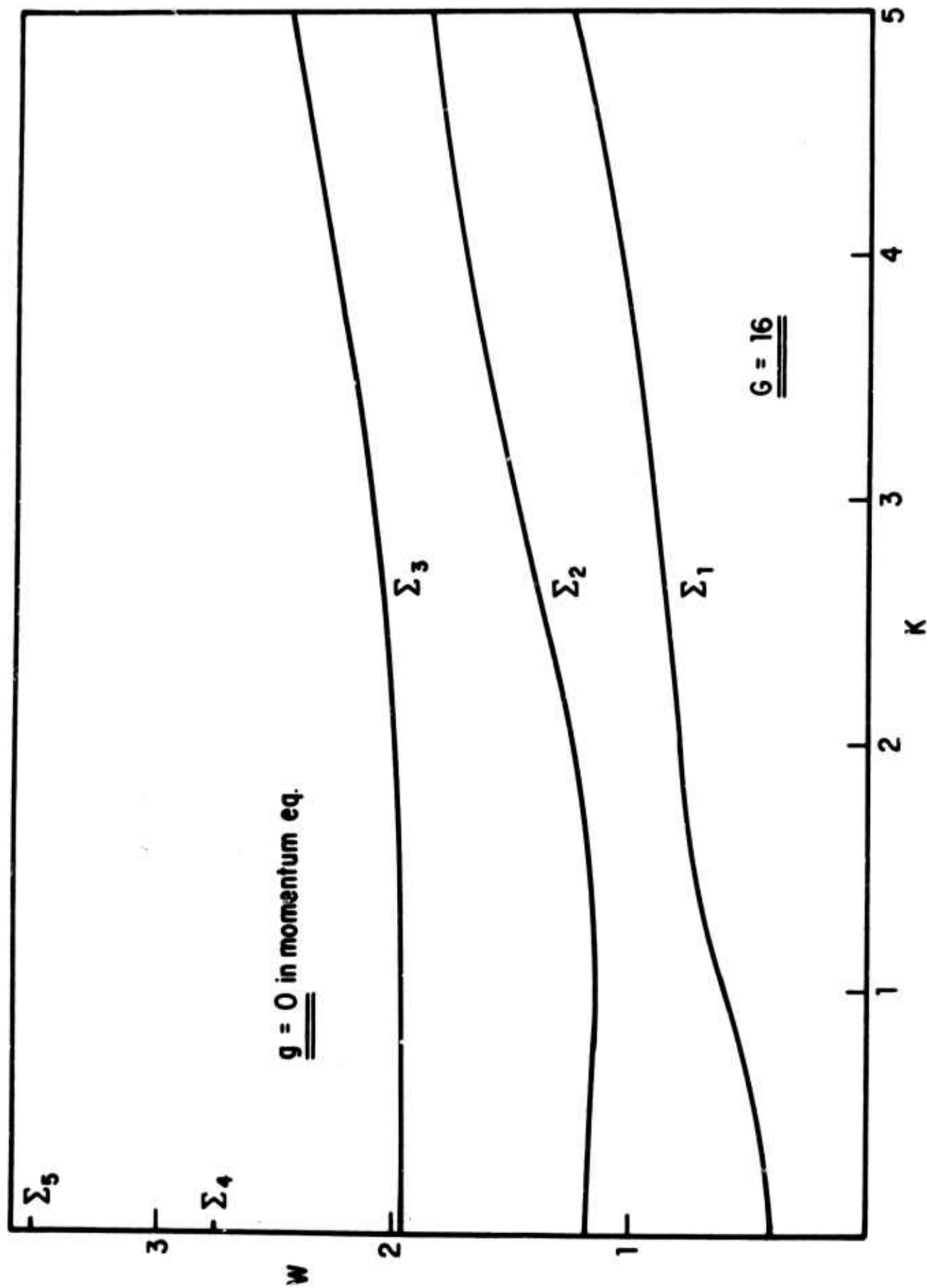


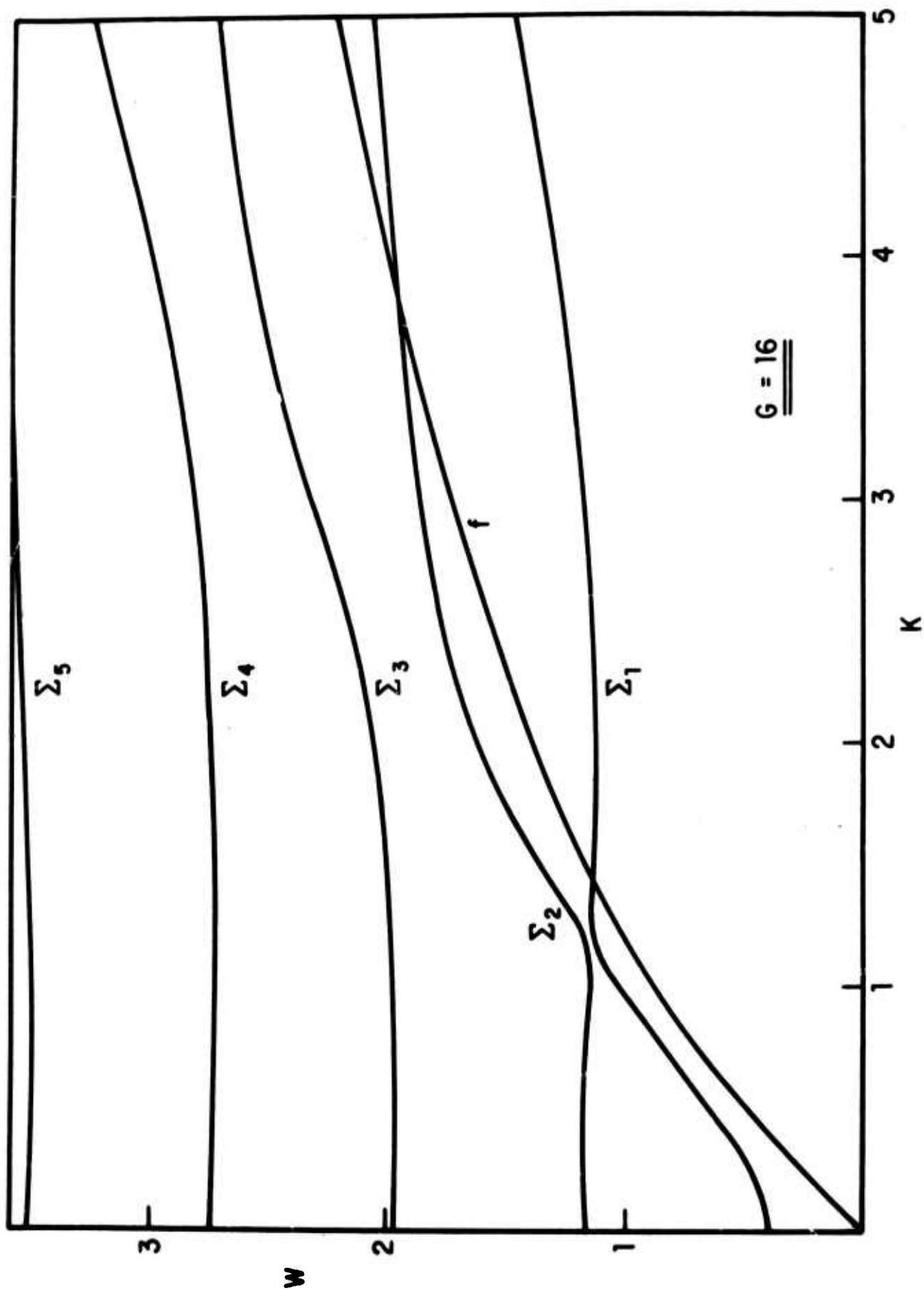


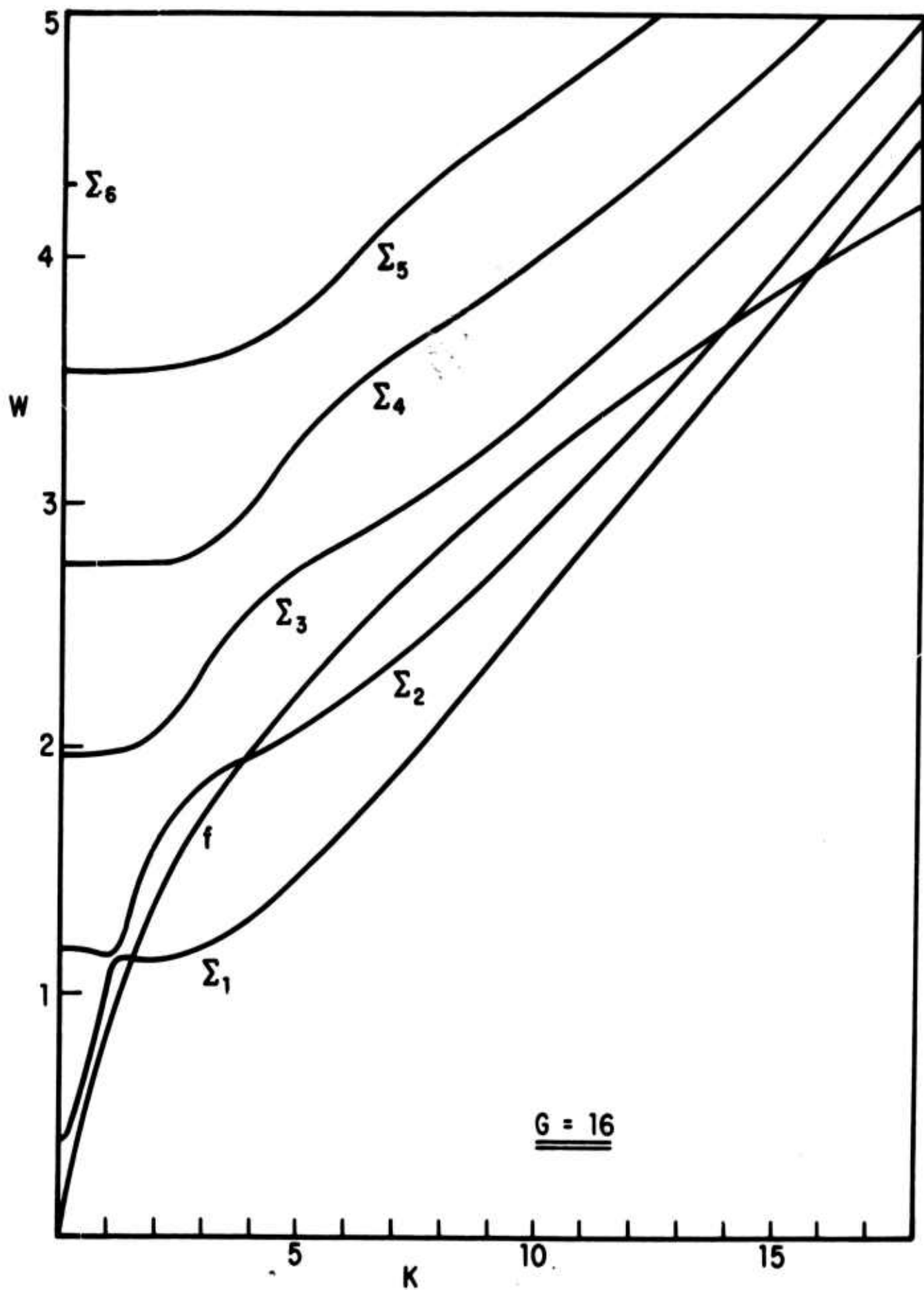


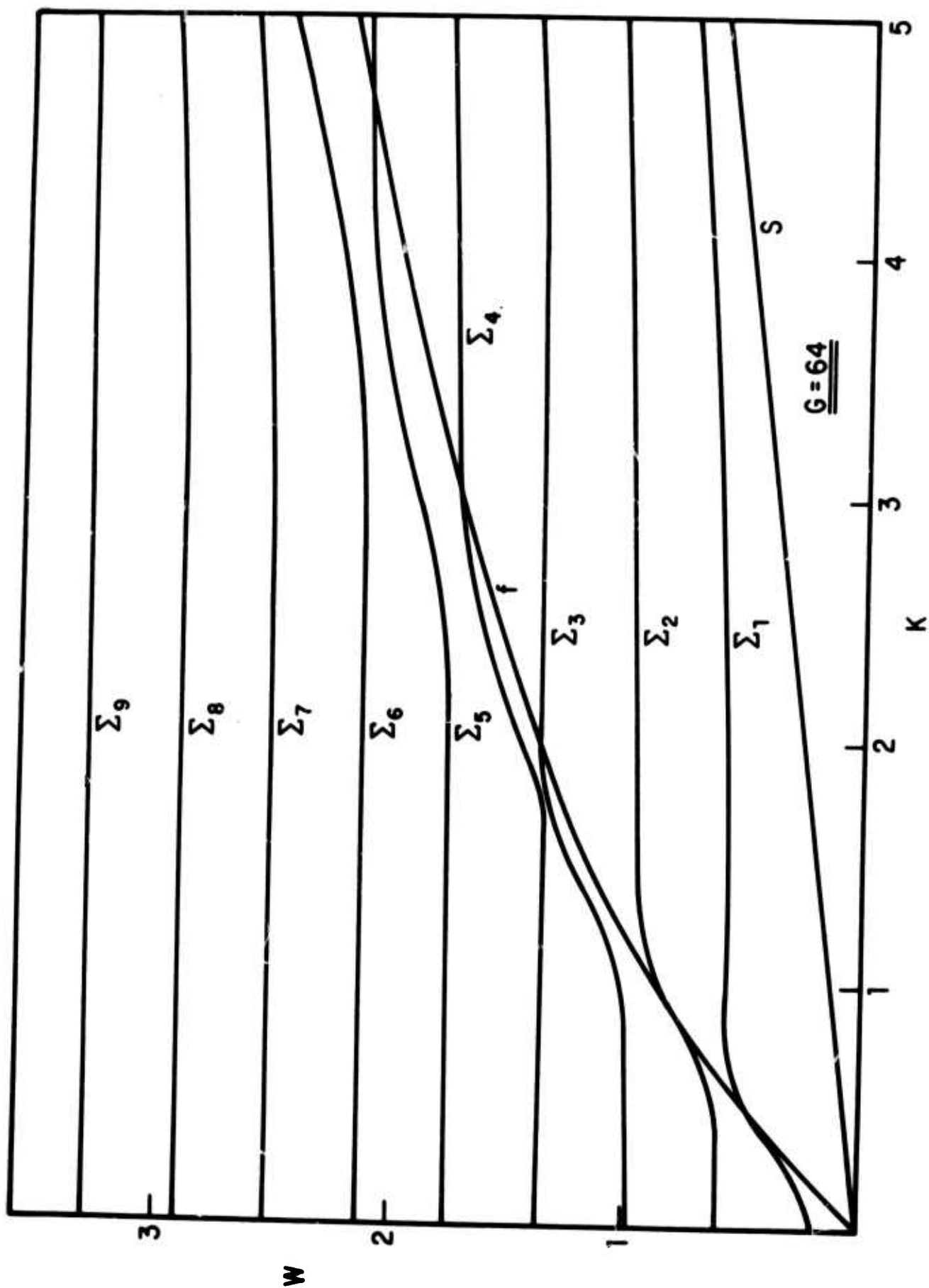












PART 2

Dr. Bradne.'s Section

DEEP OCEAN SEISMIC BACKGROUND STUDIES

This progress report will summarize some new studies of deep-ocean microseisms made with frequency-modulation recording seismographs and with new longer period seismographs.

The new instruments shown in Fig. 1 use 3 sec. free period seismometers in triaxial arrangement, with Texas Instruments Company's parametric amplifiers and 0.0075 inch/sec. direct-record magnetic tape, all housed in a 24 inch diameter bouyant aluminum pressure sphere. A 24 db/octave low-pass filter at 1/10 cps allows us to record the seismic spectrum at periods long compared with the 1/8 cps microseism peak. Timing marks are put on the tape by a Seiko crystal clock which has timing accuracy of better than 1 second per year. Magnetic tapes are transcribed by means of an Adage Ambilog computer before being digitally analyzed by the familiar BOMM time series program to get spectra, phase, and coherence between three components.

1.

BOTTOM INSTRUMENTS

Ocean bottom records with the new instruments show variable high power density below the microseism peak frequency, and strengthen our suspicion that water motion may at times dominate the microseism spectrum outside the region of the microseism peak. When the high noise does not

occur, spectra shows the familiar quiet region below the direct wave power peak. Fig. 2 shows a preliminary spectrum taken north of Hawaiian Islands three hours before the CHASE V Shot.

The conjectured effect of water motion is supported by a number of factors:

- a) The tidal current drags correspond to terrestrial winds of many miles per hour on an unprotected seismometer.
- b) Similar records have been produced by planting our instruments in protected shallow-water areas, with savonius rotor current monitors.
- c) Sutton has found direct correlation between noisy records and water currents in the deep-water Columbia University emplacement off the Northern California coast.
- d) A spectral frequency peak and low harmonics often appear on our records at frequencies appropriate to Karmann vortex flow around the instrument antenna.
- e) The conjecture is also supported by the data of Fig. 3 which shows seismic spectra from two of the f.m. recording instruments approximately 500 ft. apart in water of 20,000 ft. depth.

Note that the spectra look qualitatively similar throughout the frequency band, but that there is evidence of local noise sources since coherence is low outside the region of the microseism peak. The two instruments had previously showed greater than 0.95 coherence throughout the frequency band with a signal 1% as large, when they were run side by side on land.

The ocean-bottom coherence in the microseism peak implies that water motion is, however, not responsible for the large observed ocean-bottom peak power. The ocean/land ratio is usually taken to indicate poor energy transport toward the continents, though Sutton has recently argued that the elastic characteristics of the bottom can influence the records enough to account for the ratio (ref. 2). The following argument lends qualitative support to Sutton's view in one case at least. Fig. 4 shows land and sea spectra from records about four hours apart during uniform quiet weather at an isolated mid-Pacific island. The ocean measurements were made in 1500 ft. water depth, ten miles from Swain's Island which lies about 150 miles from the nearest significant land mass, Samoa. Swain's is a one mile diameter coral island with underwater contours and a scaled profile of the island. Even if we assume seismic wave velocity as small as 2 km/sec., then one wavelength at 1/4 cps is the size of the figure. The island base and height are small compared with the wavelength, and hence would be expected to have little effect on the seismic energy transport for frequencies below 1/4 cps. The spectrum of Fig. 4 shows that the peak land power was smaller than the peak ocean-bottom power by a factor of 100, even though the land seismometer was simply buried under a foot of loose coral in a cocoanut grove a hundred yards from the edge of the reef. The transmission characteristics from ocean to land should not account for the large power difference in this example. The elastic characteristics of the environments, however, could be significant.

2.

MIDWATER INSTRUMENTS

We have reported that ocean-bottom spectra frequently show a

series of peaks which are compatible with organ pipe modes in the ocean waveguide. We are checking the reality of the organ pipe modes by balancing an instrument to float at a predetermined depth in the ocean. Since aluminum is less compressible than sea water, our spherical instruments can be made to float at any desired depth by attaching an appropriate weight. An error of 0.01 ounce changes the floating depth of our 250 lb. instrument by about 40 ft. Ignorance of ocean temperature and salinity normally cause depth setting to be uncertain by at least 150 ft. Therefore, we make an f.m. tape record of the hydrostatic pressure. In practice we attach supplementary weight to make the instrument sink rapidly to approximately the desired depth. A rupture disk then releases the supplementary weight and allows the instrument to settle to its equilibrium depth. After a pre-determined time a conventional Van Dorn magnesium release drops the balance weight, allowing the sphere to return to the surface for normal recovery. Fig. 6 shows a mid-water instrument with supplementary weight, Van Dorn release, depth-sensing pressure potentiometer, and the balance weight made from three lead masses. These masses were mounted on an inverted tripod to lengthen the period of rocking oscillation. Fig. 7 shows simultaneous spectra from a test of an ocean-bottom instrument and a midwater instrument floating at 2,000 ft. depth in 4,000 ft. water, in the San Diego Trough. Water currents in this region are frequently the order of $1/3$ ft./sec. (ref. 3). The large peaks in the ocean-bottom spectrum at $2-3/4$ cps and $5-1/2$ cps are attributed to vortex disturbance around the antenna of the instrument. Several other sharp small peaks in the two spectra can be traced to mechanical oscillations of components inside the instrument. The large peak at $3/8$ cps in the midwater spectrum is at the rocking frequency. The San Diego Trough spectrum does not show

organ pipe modes for comparison with the midwater spectrum; but note that the low frequency power beyond the rocking peak in the midwater spectrum is far less than that in the ocean-bottom spectrum. This gives additional support to the view that water motion may produce a significant apparent seismic background. A midwater seismometer is nearly perfectly coupled to the surrounding water, and thus its motion can be directly related to the vertical component of bottom motion in the seismic frequencies of interest, unless it is disturbed by non-seismically generated water motion.

The highest frequency of internal water waves, viz., the Väisälä frequency, depends on the vertical density gradient. Internal wave periods are characteristically 1/2 hr. in the deeper parts of the ocean and are rarely shorter than one minute in even the sharpest part of the thermocline (ref. 4). The characteristic power spectrum of turbulent layers is more difficult to discuss quantitatively. Cox indicates that it will probably not be significant for periods less than about 15 minutes.

3.

CHASE V

The new direct-recording instruments were constructed and first used for the CHASE V experiment, 1 kiloton of explosive detonated 23 May 1966 at about 3,750 ft. depth in 12,500 ft water off the Cape Mendocino Coast of Northern California. We placed ocean-bottom instruments at two locations between the shot point and Hawaii, plus a land station on Oahu, Hawaii, to investigate possible generation of microseism frequency disturbance by impulsive excitation of the ocean waveguide. Analog records from a deep-water nuclear shot and from a San Clemente Island earthquake had shown a "ringing" at microseism frequency for more than an hour after the event.

Fig. 8 shows the record from the Wigwam 20-30 kiloton nuclear shot, as recorded on a vertical Galitzin seismometer at Berkeley, approximately 1,000 km away. Fig. 9 shows the record from the San Clemente Island earthquake, recorded on an E-W Galitzin seismometer at Berkeley. No theoretical calculations had been made for impulsive excitation in the San Clemente, Wigwam, or CHASE V areas. The CHASE V area was broad, flat, and relatively uniform, so we made a rough prediction of the signal by scaling to the expected CHASE V energy release and assuming similar waveguide coupling and radial propagation. Under these conditions 1 kt shot was expected to give a detectable "ringing" signal at both of our ocean stations, viz., $25^{\circ} 04.5'N$, $151^{\circ} 47.0'W$, and $22^{\circ} 25.5'N$, $153^{\circ} 09.6'W$. The two separated ocean stations would give information on waveguide propagation in the ocean environment. The land station was established on Hawaii in hopes of measuring the attenuation in signal propagation from ocean to island.

The most striking result of ocean-bottom observations on the CHASE V shot was the complete absence of detectable "ringing" at micro-seism frequency. This cannot be attributed to faulty scaling calculations, since the Columbia University ocean-bottom seismometers approximately 50 miles from the shot point showed no such "ringing" minutes after the initial signal (ref. 1).

The ocean-bottom records showed large temporal variations, but none could be associated with the shot. A hydrophone hung from the ship Yaquina (our station at $22^{\circ} 25.5'N$, 3203.1 km from the shot point) showed a strong high-frequency signal at the time of water-borne arrival, but the low-pass filter of our ocean-bottom instrument precluded our seeing it.

The water-borne arrival and a brief 2 cps signal were readily detected on the Oahu land station, which did not have a sharp low-frequency filter. Fig. 10 shows an analog play-back trace of the land record.

The 3-component land station used our triaxial one cps lunar seismometers with Astrodata amplifiers and 100 mf input filters, recorded on a Honeywell f.m. tape recorder. Spectral analysis of the three components rotated to conventional EW, NS and Z is shown in Fig. 11. Comparison of these spectra and of EW spectra during three time intervals indicates that the spectra may be valid to 1/30 cps. System noise has been found to dominate below about 1/50 cps.

Fig. 2 showed the spectrum from a portion of an ocean-bottom record three hours before CHASE V arrival. Although the two records were taken at different times, the appearance of the peaks at 0.06 cps and 0.10 cps on the ocean-bottom and land records suggests that these portions of the records are reliable.

As indicated earlier, the ocean-bottom spectra show large and abrupt changes. Some reasons are (1) operation of the seismometer centering motors as the springs cool and pull the masses against their electrical contacts. (2) There is indication that the masses may make poor electrical contact for considerable lengths of time, thereby changing the seismometer characteristics until the contact pressure is finally great enough to operate the centering motor. (3) Water currents have already been mentioned. The coupling of the single spike to the bottom might accentuate the forced oscillation amplitude. We have checked this possibility by making simultaneous records with single spike and tripod-spike anchors. Fig. 12 indicates that a spectral peak around $2\frac{1}{4}$ cps

may be significantly effected by the changed coupling.

4.

SUMMARY

New ocean-bottom seismometers and midwater floating seismometers are described. Simultaneous records of two instruments show that water motion may produce disturbances which dominate the ocean-bottom power spectrum outside the microseism peak. Records indicate that the large peak power difference between ocean-bottom and land is not due to water motion or waveguide transmission characteristics.

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Latham, Gary V., and Sutton, George, Seismic Measurements on the Ocean Floor, I ed., Bermuda area., Journal of Geophysical Research, v. 71, pp. 2545-2573 (1966).

Sutton, George, private communication.

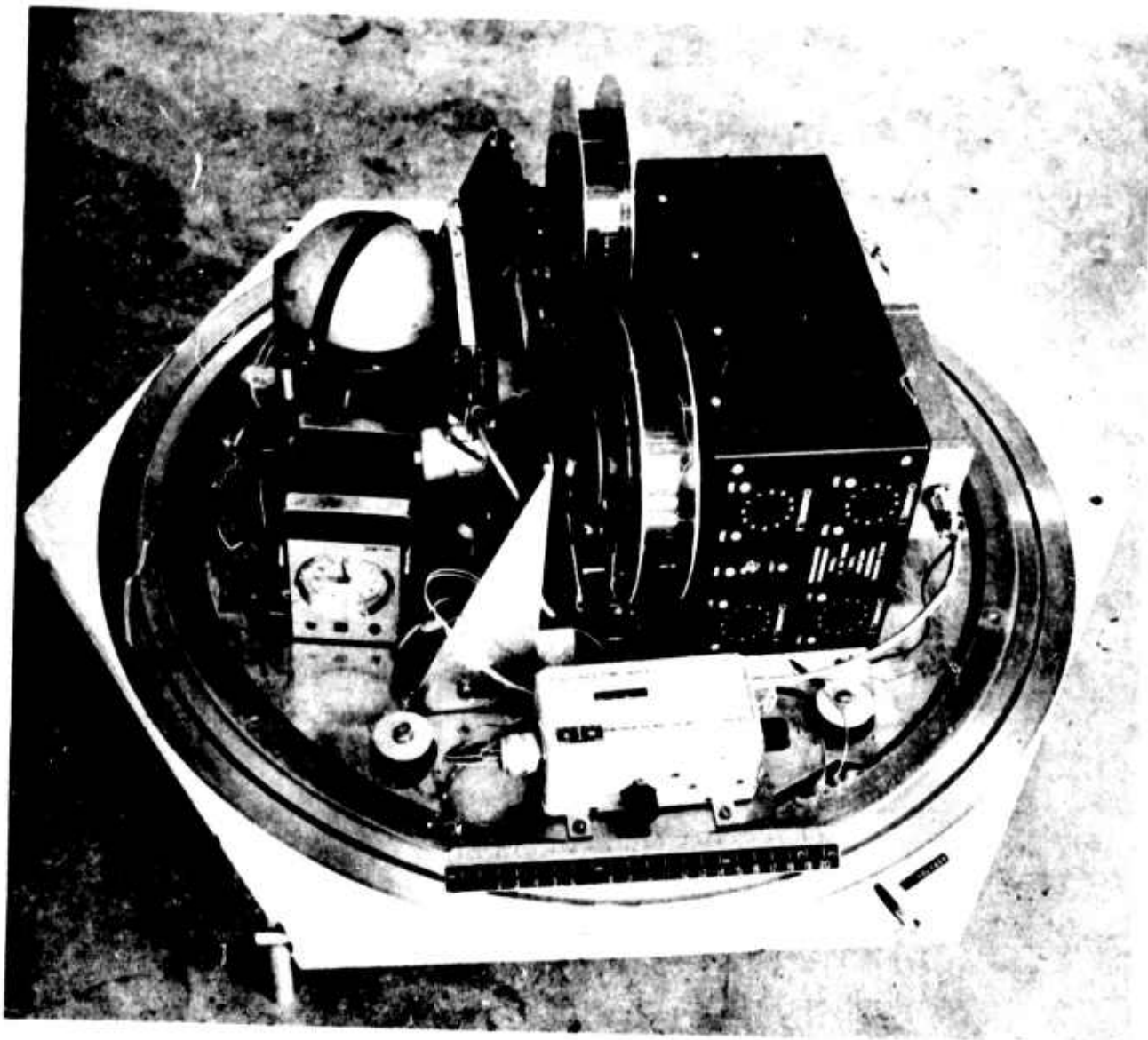


Fig. 1 Photo of direct-record ocean-bottom seismometer. Instrument contains tri-axial 3 sec. Ranger seismographs, (not visible below the hexagonal plate). Texas Instruments Co. parametric amplifiers, and 3-level direct record on Texas Instruments Co. 0.0075 i.p.s. magnetic tape. Time marks at 10/sec. and 1/sec. intervals are established by SEIKO crystal clock. Tilt and orientation are recorded by our standard device.

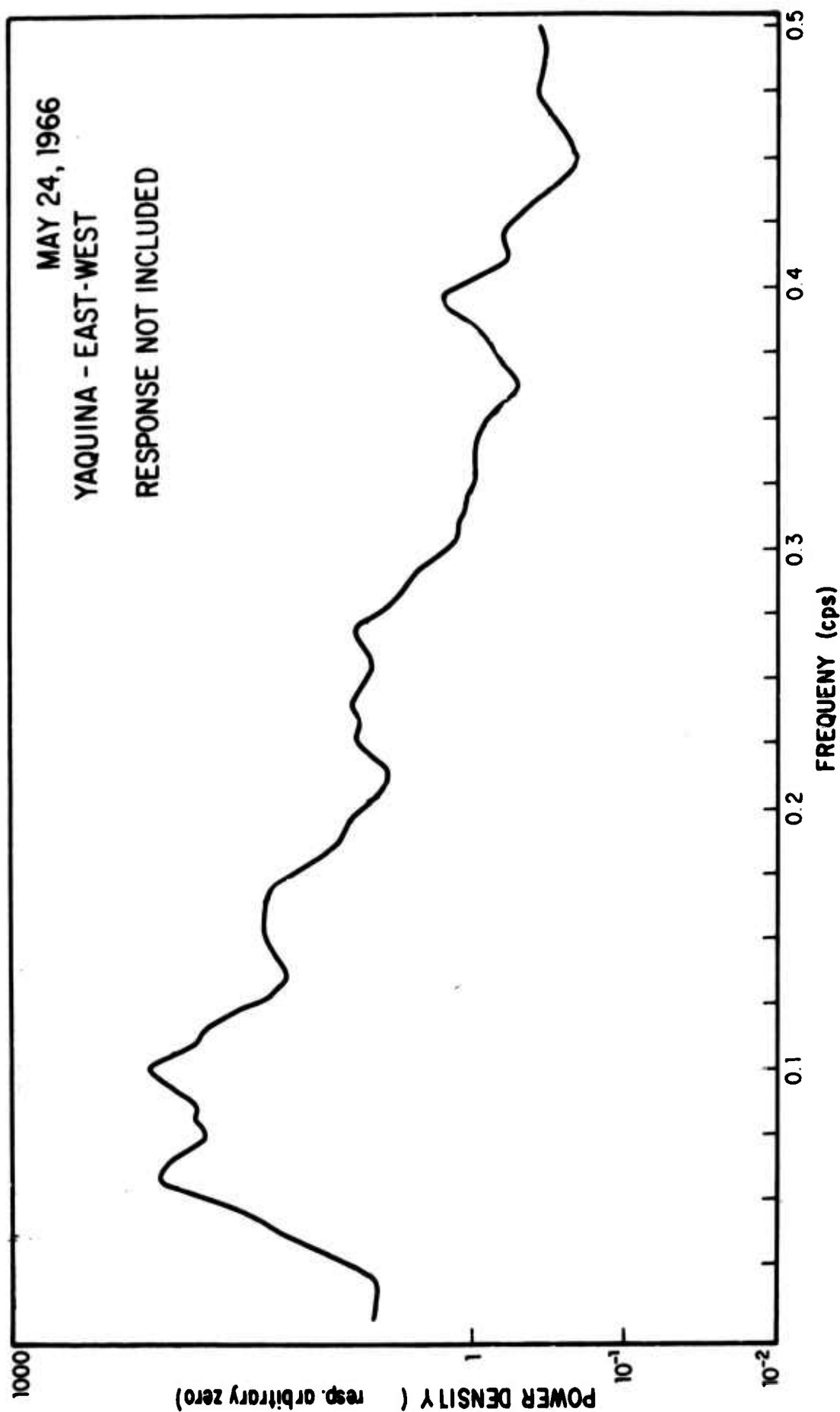


Fig. 2 Ocean-bottom spectrum with direct record long period instrument.
22° 25.5' N, 153° 09.6' W. 0222-0257Z, May 23, 1966, Approximately
three hours before CHASE V arrival.

1966 JAN 15 1800 Z
160 KM NE OF HAWAII

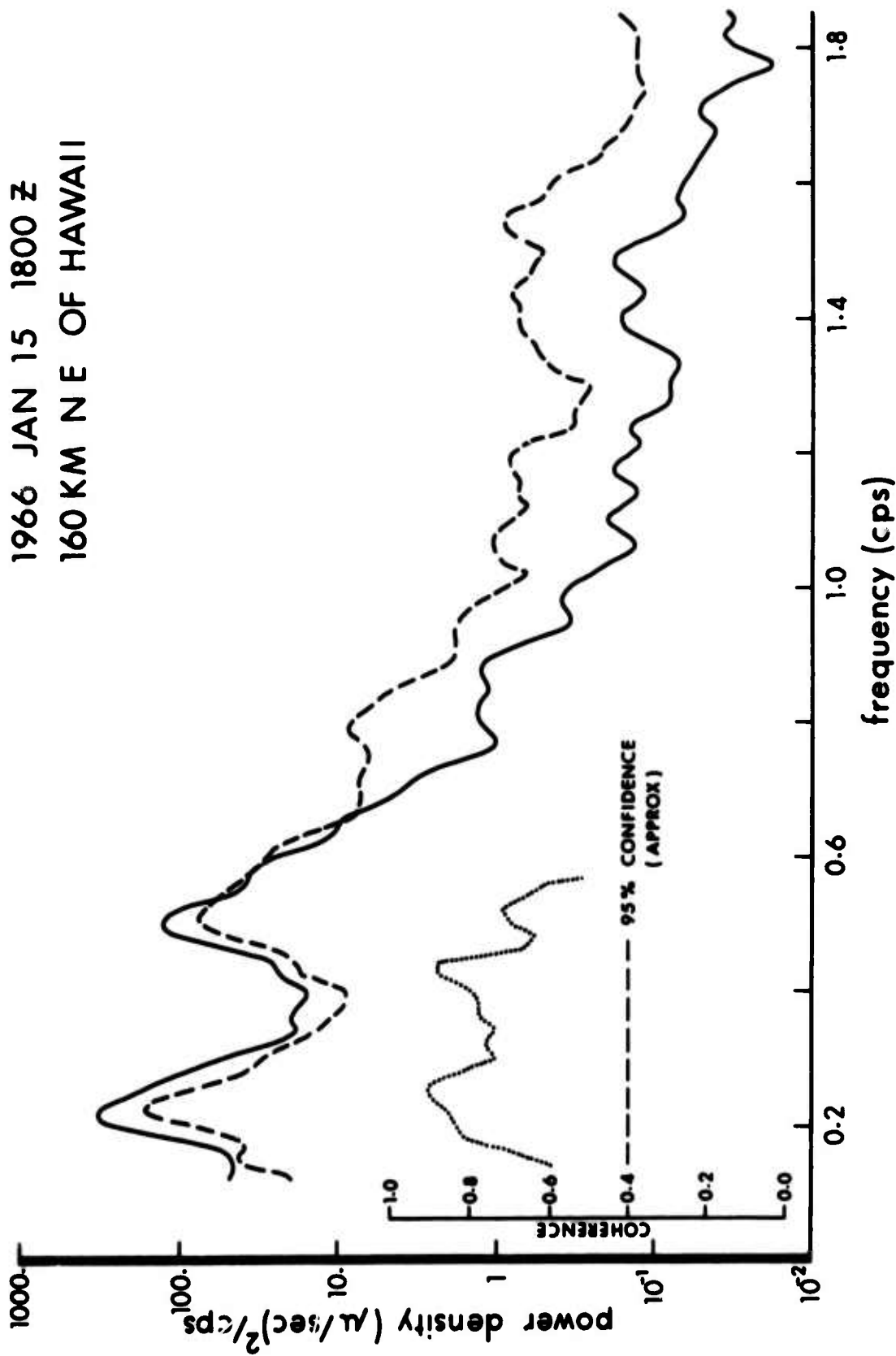


Fig. 3 Comparative spectra of two f.m. seismographs approximately 500 ft. apart. The coherence was below the 90% confidence level except for the region between approximately 0.1 and 0.6 c.p.s.

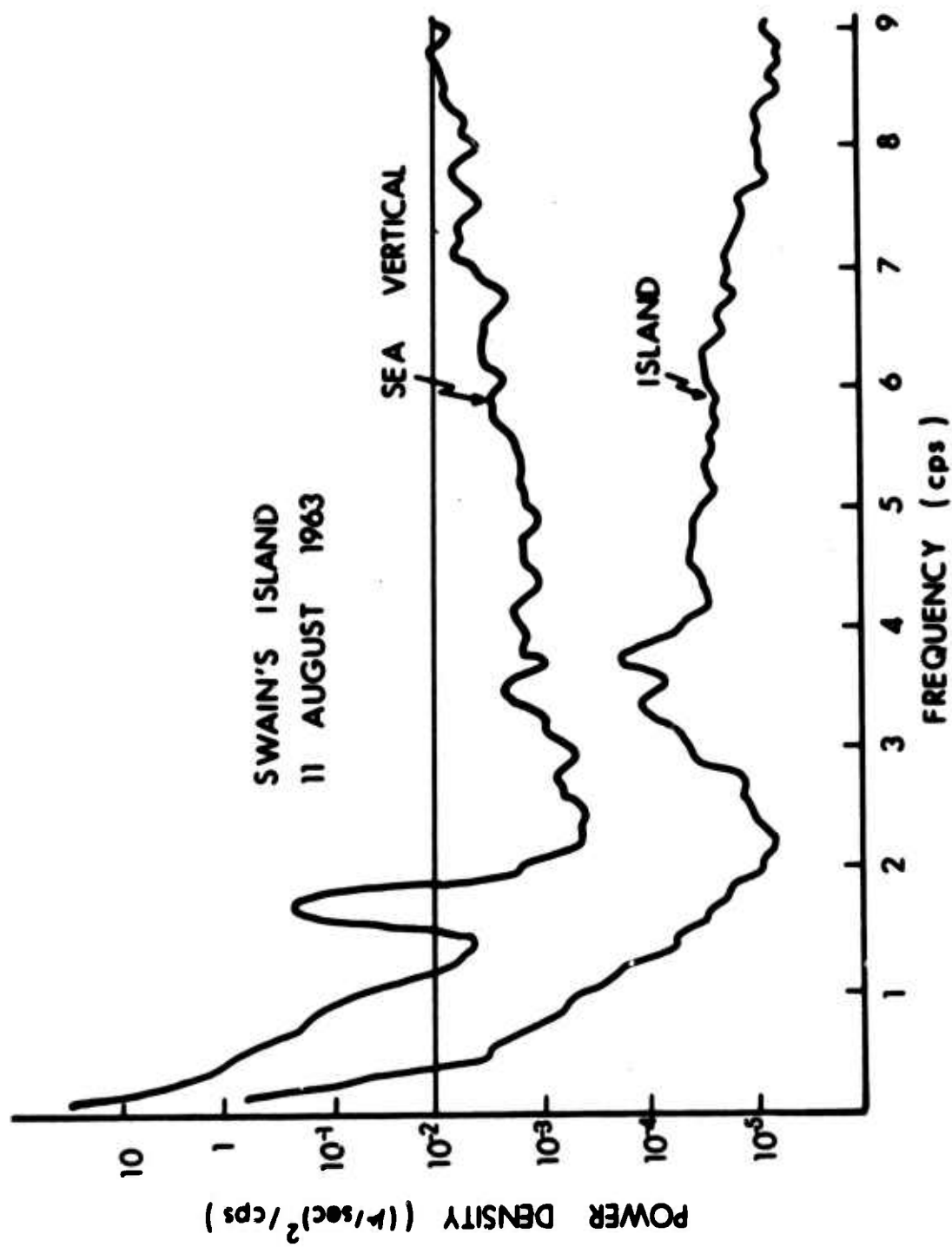


Fig. 4. Comparison of land and ocean-bottom spectra, Swain's Island.

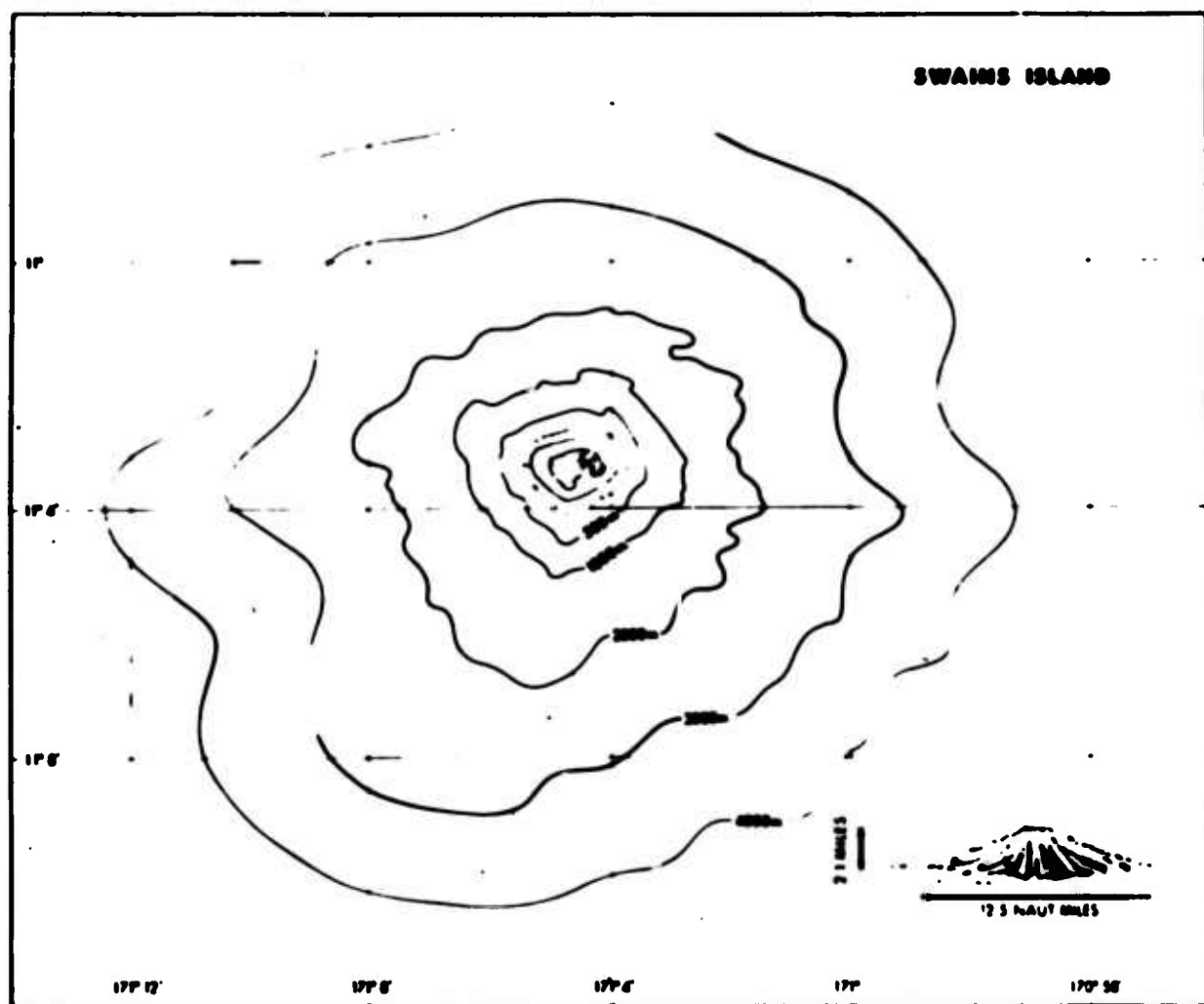


Fig. 5 **Depth Contours, Swain's Island.**

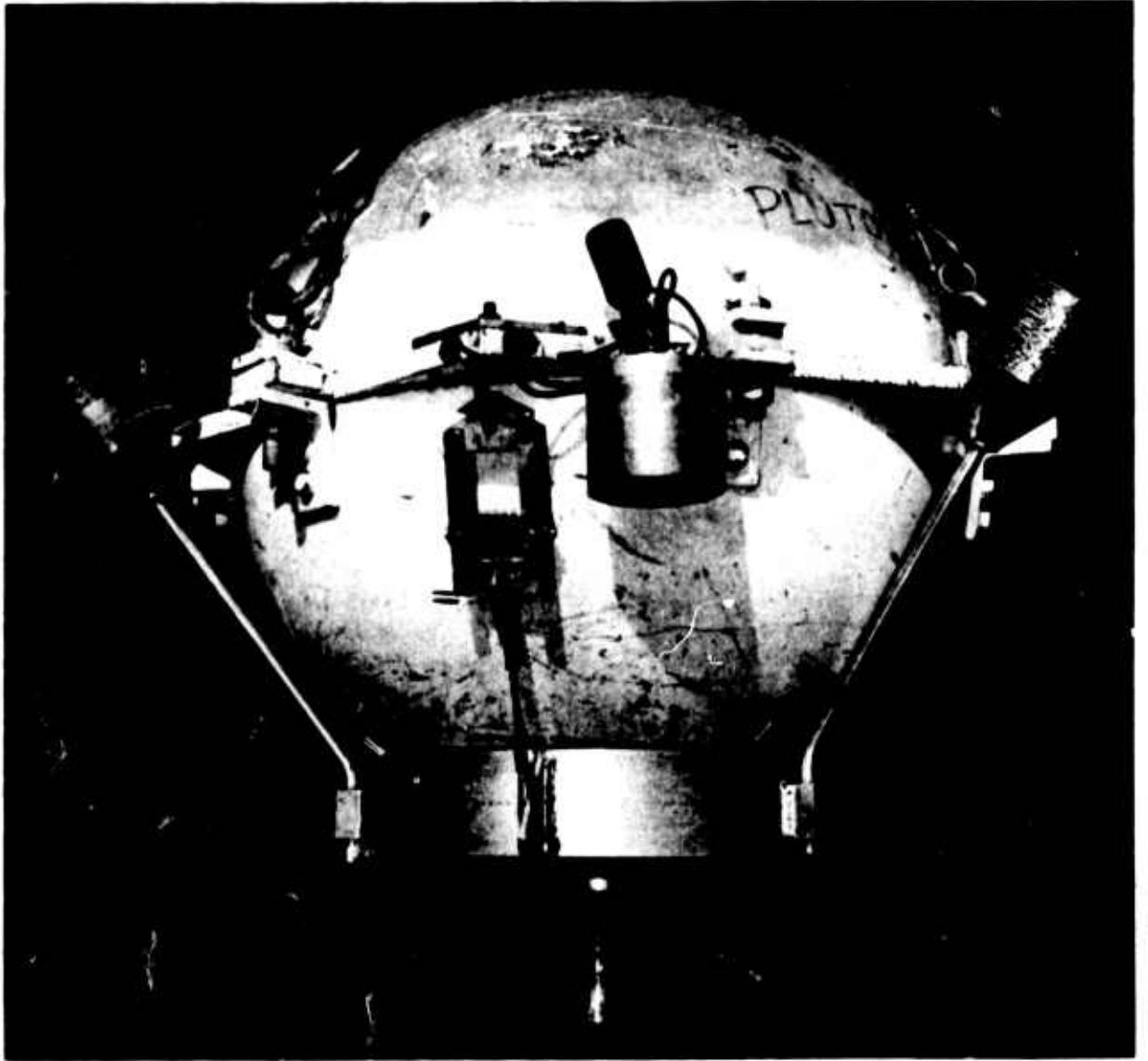


Fig. 6 Mid-water seismometer, showing pressure potentiometer and Van Dorn release.

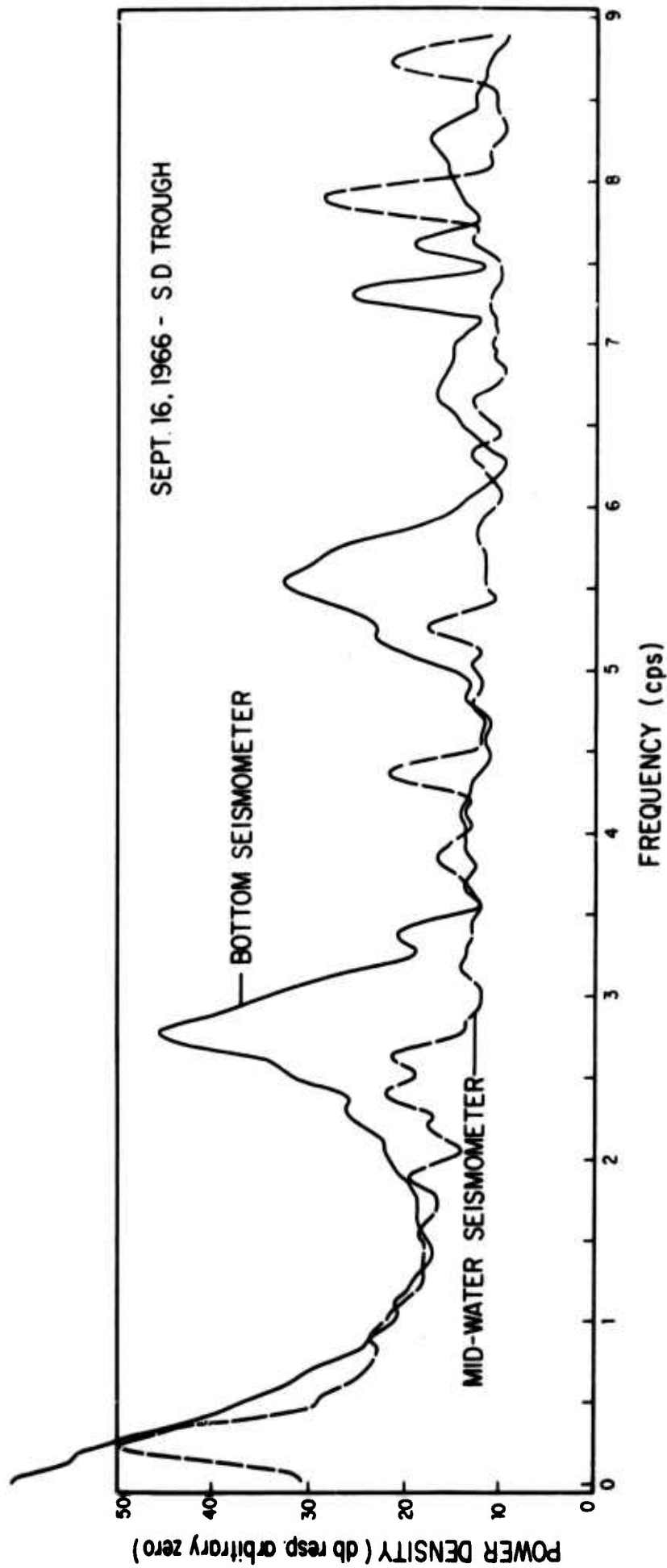


Fig. 7 Comparison of Ocean-bottom and mid-water spectra. San Diego Trough
September 16, 1966.

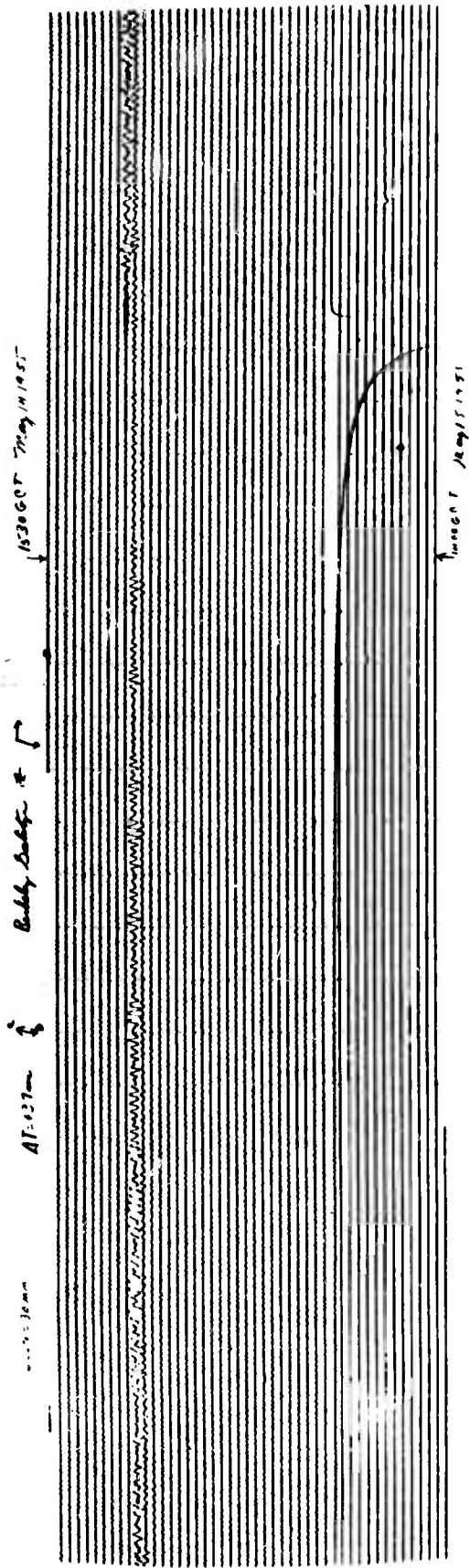


Fig. 8 Vertical Galitzin Seismometer trace of underwater nuclear shot May 14, 1955. (Courtesy of University of California, Berkeley Seismology Laboratory.)

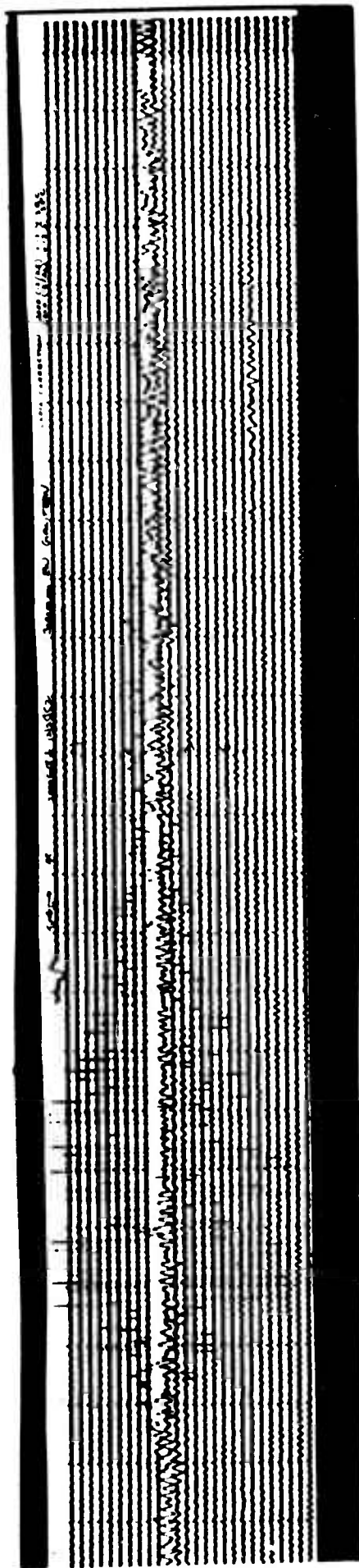


Fig. 9 East-West Galitzin seismometer trace of San Clemente earthquake
December 25, 1951. (Courtesy of University of California,
Berkeley Seismology Laboratory.)

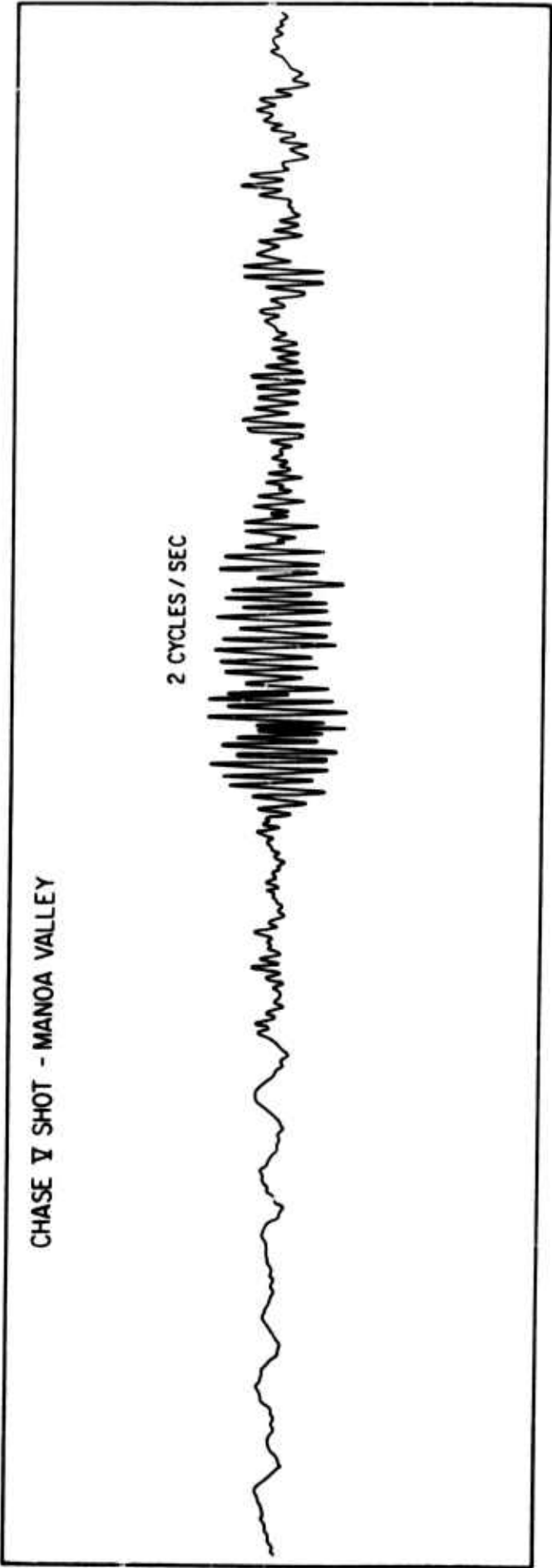


Fig. 10 CHASE V Shot. Land record, Oahu, Hawaii.

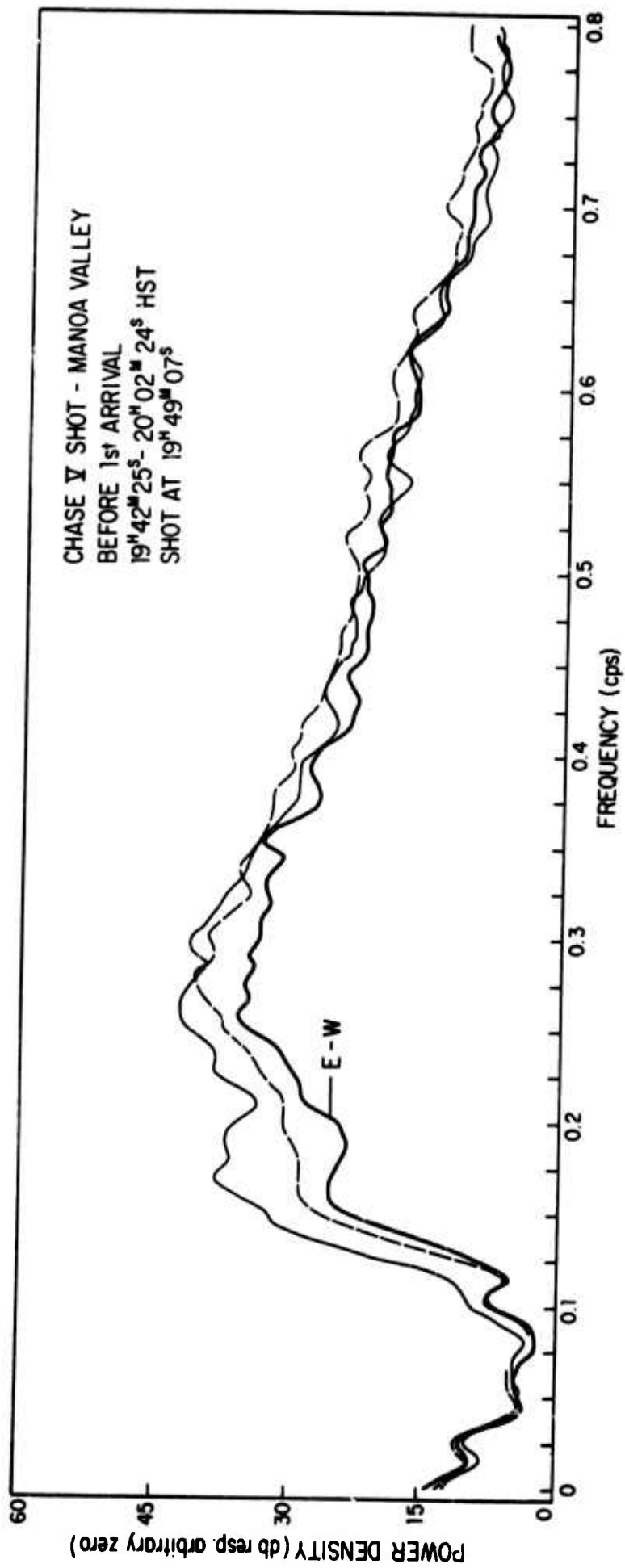


Fig. 11 Background spectrum just before CHASE V first arrival,
Oahu, Hawaii land station.

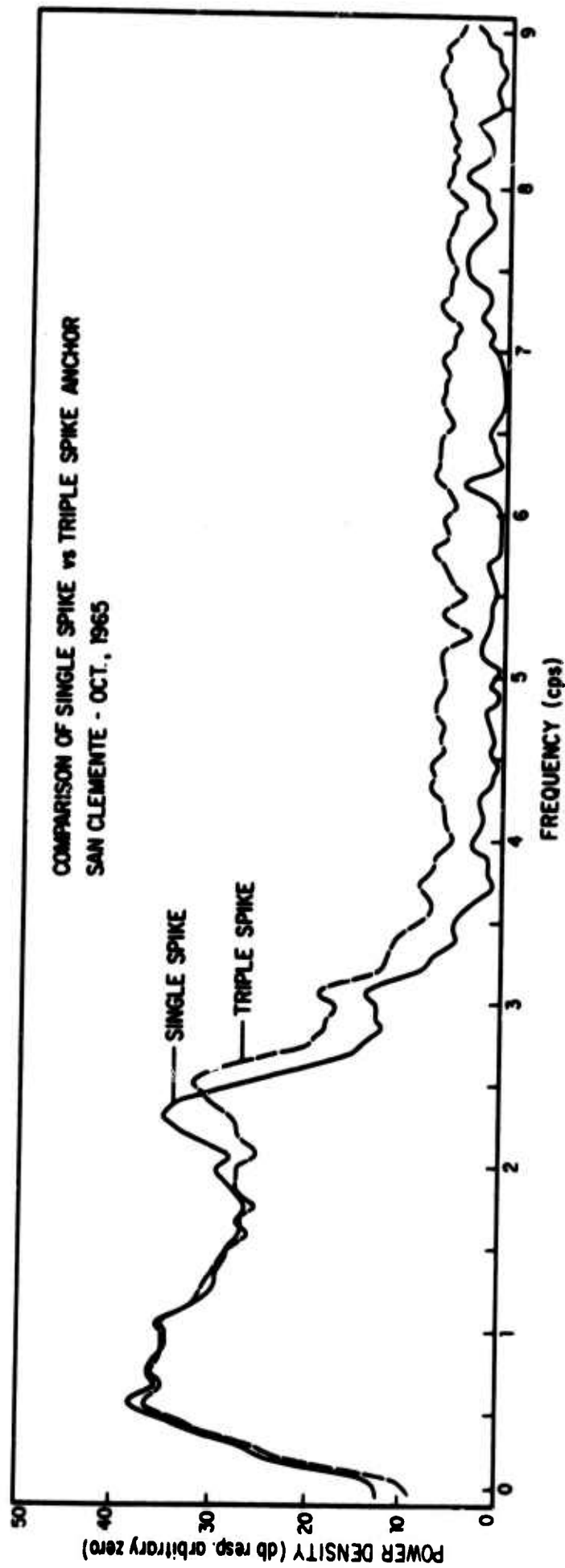


Fig. 12 Comparative spectra of single-spike and tripod-spike instruments, planted approximately 100 ft. apart.

PART 3

William Farrell's Section

THE GYROSCOPIC SEISMOMETER

1. Introduction

The Pendulous Electric Vacuum Gyro (PEVG) Seismometer, designed & built at the General Motors Defense Research Laboratories, Santa Barbara, California, has been running in the Institute of Geophysics & Planetary Physics Seismic Vault since November 1966; the continuous recording of data commenced on 11 February 1967. The noise level in the instrument has been measured and a number of electronic difficulties corrected. Tests are continuing on (a) the instrument response to low-frequency displacements with known time histories, and (b) the separation (theoretically perfect) of tilts from horizontal accelerations.

2. Description

PEVG SEISMOMETER

The PEVG Seismometer consists of a pair of contrarotating pendulous gyroscopes mounted on a rigid plate. The fundamental idea behind the instrument is that horizontal accelerations deflect the two spin axes in opposite directions while tilts give apparent deflections, relative to the base, in the same direction. This capability of distinguishing tilts from horizontal accelerations is unique among seismological instruments, and is due to the fact that measurements are made with respect to an inertial frame of reference rather than a relative frame of reference

fixed at some point on the surface of the earth. The gyroscopes are basically the same as those developed for many years at the General Motors Defense Research Laboratories for navigational purposes.

Each gyroscope is a one inch diameter Beryllium shell, supported inside a glass case by electrostatic fields and spinning at 800 cps. The lower hemisphere is slightly heavier than the upper, so that the center of mass is located .2 cm beneath the center of figure. Inscribed around the equatorial surface are 120 lines, great circle arcs inclined 30° to the equator. Four optical sensors, consisting of a light source and photo transistor, are equally spaced around the equator of the glass case. The light intensity is modulated at 96.156 kc, and since lines cross the illuminated spot at 96 kc, the reflected light, measured by the photo transistors, has a 156 cps modulation (this is referred to as the IF). The position of the spin axis in the vertical plane through diametrically opposed optical pickoffs, is proportional to the phase shift between the two IF signals. The phase shift is measured by a conventional time interval counter which sequentially samples the four pairs of outputs. The phase difference for each pair is averaged over one second so the sample rate for a given axis is .25 samples/sec. The data is recorded digitally on magnetic tape. With this system, the direction of the gyro spin axis can be measured to a fraction of 1 $\overline{\text{sec}}$.

Mathematically, the pendulous gyros behave like simple long period pendulums, except that horizontal accelerations cause an initial deflection normal to the acceleration, and the motion is circular rather than linear. The precessional motion is lightly damped ($Q \sim 70$) by a

vertical magnetic field.

A complete description of the instrument is given in the Final Report on a D.C. Shift Seismometer, General Motors Defense Research Laboratory Report No. TR66-23 which is available from the Defense Documentation Center.

3.

NOISE MEASUREMENTS

At present, 70% of the noise power is contained in a narrow band and is coherent between all four channels. The center frequency of the band corresponds to the difference frequency between the IF's of the two gyros, and the noise is caused by an electronic coupling between the various circuits. The obvious way to eliminate the noise is to make the IF's exactly equal, i.e., spin each gyro at precisely the same speed, and the modifications for achieving this are underway.

Ignoring this narrow band noise, the rest of the spectrum is flat from .1 to 125 mcps on all four channels, but the noise power varies from $1.5 \times 10^{-3} \text{ sec}^2/\text{mcps}$ on the best channel to $3 \times 10^{-2} \text{ sec}^2/\text{mcps}$ on the worst. This noise arises in the photo transistors. It may be possible to replace the solid state detectors with photomultipliers, and the expected gain of 20 db in the signal to noise ratio should bring the noise power near to the Brownian limit.

PART 4

Dr. Carl Hubb's Section

CRUISE MV66 - II (U. S. NAVY OPERATION - CHASE V)

Report Compiled and Presented by

Robert L. Wisner (Chief Scientist)

1 March 1967

NARRATIVE REPORT ON CRUISE MV66 - II (U. S. NAVY OPERATION - CHASE V)

18-27 May, 1966

Robert L. Wisner (Chief Scientist)

Cruise MV66 - II was undertaken on the Scripps vessel, the R/V ALEXANDER AGASSIZ, to do biological work for the U. S. Navy Operation CHASE-V. This operation, the fifth of a series designed to dispose of outdated munitions and other explosive materials (exclusive of casings and packaging) into a condemned C-3 Liberty vessel which was to be sunk and exploded at a depth of 4000 ft. The C-3 was towed by a Navy tug from the Puget Sound area.

The task of the Scripps party was to evaluate the effects of the blast on marine life, particularly on the fishes. Toward this end a sampling program was drawn up, to cover all depths from surface to bottom, before and immediately after the explosion.

The officially designated site of the explosion, $40^{\circ} 36' \text{ N.}$, $125^{\circ} 45' \text{ W.}$, was over an abyssal plain of some 2900 meters depth, about 12 miles north of the Mendocino Escarpment and 78 miles westerly of Cape Mendocino, California. Unfortunately, rough seas at this site during the night of 22-23 May caused the C-3 to break loose from the tug. The seas were too high to permit recovery of the tow and it drifted southward toward shipping lanes and undersea communication cables.

Naval authorities decided to explode the vessel when and if a scuttling party could be put aboard. Late in the afternoon of 23 May, after several attempts, two of an intended four-man party boarded and at 1817 (PDST) reported scuttling procedures completed. At 2249 (4 hours, 32 minutes later) the C-3 exploded over about 3600 meters of water south of the Mendocino Escarpment at ca. $39^{\circ} 28.8' \text{ N.}$,

125° 46' W., some 12 hours after the scheduled time and 66.5 miles south of the intended site.

The AGASSIZ was about 5.2 miles south of the site of detonation. The shock wave was quite severe but no damage was sustained. Several heavy after shocks, in very rapid succession, were felt. Darkness and distance precluded any observation of surface disturbance or of plume resulting from the explosion.

RUNNING NOTES ON CRUISE MV66 - II

(Operation CHASE - V)

Departed San Diego at 1200 (PDST), 18 May 1966, and arrived at the scheduled explosion site (40° 36' N., 125° 45' W.), at 0855 21 May. Excellent speed was made enroute by "dog-barking" (near-shore navigation from point to point of land). This method takes advantage of north-flowing currents inshore of the south-flowing offshore California Current.

In the immediate vicinity of this work site, two non-closing Isaacs-Kidd midwater trawls to 2,000 meters, one 16-foot otter trawl and two free-vehicle set-lines were made to the bottom to 3,000 meters. The two midwater trawls took relatively few fishes but many invertebrates, principally coelenterates. The otter trawl took no fishes and but few invertebrates. The two free-vehicle set lines took but five macrourid fishes (family Coryphaenoididae). Traps attached to the set lines took no hagfishes or amphipods.

These collecting efforts were completed by 1630, 22 May, by which time winds had reached 25 to 30 miles per hour. The steep, short-period swell that had developed rendered further work quite hazardous to personnel and equipment. The vessel was hove-to overnight, under steerage, to await the possible abatement of wind and sea. However, weather conditions had worsened overnight and no further

work was attempted the following day. Shortly after noon, 23 May, the C-3 was reported to be adrift and that it would be exploded when a scuttling party could be put aboard. Following the explosion (described above) sea conditions prevented the launching of gear to sample fish life in the immediate vicinity of the explosion. Thus it was not possible to assay any damage, and the prime purpose of our participation in the operation was obviated. In lieu of towing collecting gear I proceeded to the area to look for dead fish at the surface. Nothing, save one fish, floating belly-up, was seen during an hour of searching. This fish may have been a hake or a salmon; darkness and greatly limited visibility and a rough, wind-streaked surface precluded any attempt to maneuver and collect the one fish seen.

Prior to darkness, in the general area of the explosion, the only surface animals observed were a few black-footed albatross (Diomedea nigripes), four Pacific striped, or white-sided, dolphins (Lagenorhynchus obliquidens) and several female Alaskan fur seals (Callorhinus ursinus); one of these was playing near the AGASSIZ about three hours prior to the explosion.

The search for surface kill was abandoned at 0030, 24 May. As weather reports indicated no possibility of improved sea conditions for the next several days, I proceeded southeasterly to off Point Reyes to attempt further work.

At this locality ($38^{\circ} 00' N.$, $124^{\circ} 11' W.$), although sea conditions were still marginal for work, collections were obtained by two midwater trawls (to 1500 meters), and by two free-vehicle set-lines, at depths of 3363 and 3422 meters, respectively. The two midwater trawls took excellent catches of fishes, plus a large amount of invertebrates. Fishes of unusual interest included an apparently new species of rattail (Coryphoenoides sp.), one specimen of which was taken, very unexpectedly, some 1860 meters off the bottom; a new barracudina

(Stemonosudis sp.); 2 adults of the rare witch eel, Venefica tentaculata; a very peculiar slickhead, Leptochilichthys agassizii, previously known from one specimen taken long ago near Panama; an example of a very peculiar and rare pelagic fish, Eutaeniophorus festivus, not previously taken close to California, and various other rarities.

The two set lines took 7 rattails (Coryphaenoidid fish) of 3 species (one new to science and another hitherto unknown so far north), one eelpout, of a rare and likely new species, and a small soupfin shark (Galeorhinus zyopterus). No hagfish or invertebrates were in the traps. Due to rough seas these set lines were not recovered until 1300, 25 May.

This was the last work done on the expedition. Since 23 May, a ship's officer had been suffering from an infected elbow. Radio contact with the Scripps Medical Officer, morning of 25 May, resulted in orders to proceed to San Francisco to hospitalize the officer and await a replacement if further sea work was to continue. Contact with the Director's Office at Scripps resulted in a decision to proceed directly to San Diego, as the weather prognostications indicated that time and effort would be wasted by returning to the area of the explosion. Also, so much time had elapsed since the explosion that searching for dead and injured fishes would be futile.

The AGASSIZ arrived at San Diego at 0930, 27 May.

Although the emergencies involved rendered it impossible to follow effectively the program designed to evaluate the effects of the blast on marine life, the extraordinarily rich collections that were made very materially add to our understanding of the deep-water fauna of northern and central California.

Preliminary identifications of the fishes caught in the mid-water trawls are listed in Appendix B. Large numbers of invertebrates were also obtained. The

few fishes caught on the set-lines are mentioned above.

Dr. Carl L. Hubbs has collaborated in the preparation of this report and approves it.

SCIENTIFIC PERSONNEL ON CRUISE MV66 - II

Robert L. Wisner, Chief Scientist

Joseph F. Gantner, Scripps Librarian (volunteer)

Donald M. Dockins, Curatorial Assistant

Jerry B. Graham, Marine Technician

John A. Hardy, Marine Technician

Allan J. Stover, Jr., Marine Technician

Fritz Ohre, Volunteer

Appendix A

DATA ON THE FOUR ISAACS-KIDD NON-CLOSING MIDWATER TRAWLS

TAKEN DURING OPERATION CHASE-V, U. S. NAVY

(All times listed are Pacific Daylight Saving Time)

I. Locality: $40^{\circ} 36' N.$, $125^{\circ} 45' W.$ to $40^{\circ} 39' N.$, $126^{\circ} 09' W.$
Date: 21 May 1966 Time: 0921-1620 hours

As the C-3 was to be exploded at a depth of about 1200 meters, this trawl (termed an "undulating" trawl) was designed to collect fishes near this depth, primarily.

The wire was rapidly payed out to 3500 meters (MWO) before slowing ship and winch speeds. With the ship proceeding at about 3 knots, the wire was then slowly paid out (at rate of about 18 meters per minute) to a total of 5757 MWO (nearly all the wire available) and immediately started back in at the same speed to complete one undulation through the strata.

The trawl was retrieved to 3100 MWO before being hauled rapidly to the surface.

An attached depth recorder indicated the depths fished during the undulation to have been about 900 to 1540 meters. No doubt a few fish were collected during the rapid retrieve of the last 3100 MWO.

II. Locality: $40^{\circ} 35' \text{ N.}, 125^{\circ} 51.5' \text{ W.}$ to $40^{\circ} 38.8' \text{ N.}, 125^{\circ} 49' \text{ W.}$ to $38^{\circ} 22' \text{ N.}, 125^{\circ} 50.2' \text{ W.}$

Date: 21-22 May 1966 Time: 2003-0640 hours

This was a double undulation through essentially the same water. At a ship's speed of 3 knots, the wire was slowly paid out to 3000 MWO and immediately retrieved at rate of about 18 meters per minute. When the trawl surfaced after the first undulation the ship completed a 180° turn before the trawl was started back down on the second undulation. The depth recorder indicated a maximum fishing depth of 800 meters.

The purpose of the 180° turn was to end the trawl near the site of two free-vehicle set-lines, launched just prior to the beginning of the trawl and due to surface at about 0700.

III. Locality: $32^{\circ} 01.8' \text{ N.}, 124^{\circ} 10.8' \text{ W.}$ to $32^{\circ} 22.6' \text{ N.}, 124^{\circ} 02.7' \text{ W.}$

Date: 24 May 1966 Time: 1005-1916 hours (?)

This, termed a "step-up" trawl, involved the rapid payout of wire to 5500 MWO. This length was then held for 30 minutes before slowly (about 33 meters per minute) winding in to 5000 MWO during a 15-minute period, and again holding for 30 minutes. These steps---winding 500 meters and holding for 30 minutes---were repeated to 1500 MWO. From here to the surface the wire was wound in steadily at about 33 meters per minute, in order to permit the launching of two free vehicle set lines by dark.

The depth recorder indicated that the trawl fished from about 1500 meters to the surface.

IV. Locality: $38^{\circ} 24' N.$, $124^{\circ} 06.6' W.$ to $38^{\circ} 41' N.$, $124^{\circ} 25' W.$

Date: 24-25 May 1966 Time: 2102-0710 hours

This, a step-down trawl, was essentially a reverse of the procedure used in Trawl III. Here, the first hold (for 30 minutes) was at the 500 MWO point. After the hold, the wire was paid out to 1000 MWO, in 15 minutes, and held for 30 minutes, etc., until 5500 MWO was reached and held for 30 minutes. The trawl was then wound steadily in at top winch speed, after the ship speed was slowed to compensate for the winding speed of the winch.

The depth recorder indicated a maximum fishing depth of 1500 meters.

Appendix B

SPECIES LIST OF FISHES TAKEN IN FOUR ISAACS-KIDL 10-FT MIDWATER TRAWLS DURING OPERATION CHASE-V OF THE U. S. NAVY

Species	Trawls (see App. A)				Total for Species
	I	II	III	IV	
SLICKHEADS					
Talismania bifurcata	3	1	1	3	8
Leptochilichthys agassizii	..	..	..	1	1
DEEPSEA SMELTS					
Nansenia candida	..	1	..	..	1
Leuroglossus stilbius	..	2	..	..	2
Bathylagus pacificus	9	21	7	4	41
" milleri	1	6	..	3	10
" ochotensis	7	25	14	3	49
Macropinna microstoma	..	2	..	..	2
LIGHTFISHES					
Cyclothone signata	31	110	92	118	351
" atraria	45	51	30	32	158
" acclinidens	18	48	52	38	156
" pseudopallida	5	21	11	10	47
" pallida	..	1	8	1	10
" alba	1	1	1	2	5
Sternoptyx diaphana	..	..	2	..	2
Argyropelecus pacificus	..	..	1	..	1
" hawaiiensis	..	..	..	1	1
SCALELESS DRAGONFISHES					
Bathophilus flemingi	..	1	..	..	1
Tactostoma macropus	..	12	1	11	24
VIPERFISHES					
Chauliodus macouni	9	39	9	12	69

Appendix B (cont.)

Species	Trawls (see App. A)				Total for Species
	I	II	III	IV	
LANTERNFISHES					
Hierops crockeri	6	3	3	24	36
" thompsoni	3	15	5	7	30
Tarletonbeania crenularis	6	39	20	6	71
Symbolophorus californiensis	1	..	..	..	1
Diaphus theta	..	5	8	21	34
Stenobranchius nannochir	3	4	..	..	7
" leucopsarus	14	91	18	49	172
Lampanyctus ritteri	3	17	6	..	26
" regalis	..	..	2	4	6
Parvilux ingens	..	..	3	..	3
BARRACUDINAS					
Stemonosudis, n. sp.	..	1	..	..	1
DAGGERTOOTHES					
Anotopterus pharao	2	..	..	..	2
PEARLEYES					
Benthalbella dentata	..	..	1	..	1
WHALEFISH					
Cetostomus regani	..	..	..	1	1
RIBBONTAILS					
Eutaeniophorus festivus	..	1	..	..	1
SNIPE EELS					
Nemichthys scolopaceus	..	1	..	..	1
Cyema atrum	1	..	2	2	5
WITCH EELS					
Venefica tentaculata	..	..	..	2	2

Appendix B (cont.)

Species	Trawls (see App. A)				Total for Species
	I	II	III	IV	
BIGSCALES					
Melamphaes lugubris	..	5	3	3	11
Poromitra crassiceps	..	9	4	14	27
Scopeloberyx robusta	1	..	5	..	6
RATTAILS					
Coryphaenoides, n. sp.	1	..	1
" sp. (juv.)	..	2	..	1	3
LEFTEYED FLOUNDERS					
Citharichthys sordidus	..	1	3	1	5
" stigmaeus	..	2	..	..	2
RIGHTEYED FLOUNDERS					
Microstomus pacificus	..	2	..	..	2
Glyptocephalus zachirus	3	3
SCORPIONFISHES					
Sebastodes sp. (juv.)	..	29	2	10	41
Sebastolobus altivelis	..	6	..	2	8
SABLEFISHES					
Anoplopoma fimbria	..	1	..	..	1
SCULPINS					
Scorpaenichthys marmoratus (juv.)	1	1
SNAILFISHES					
Nectoliparis pelagicus	..	2	..	..	2
Careproctus, n. sp.	..	6	..	1	7
<hr/>					
TOTAL SPECIES	20	37	29	32	53
TOTAL SPECIMENS	169	582	315	391	1457

SUPPLEMENTARY

INFORMATION

UNIVERSITY OF CALIFORNIA

INSTITUTE OF GEOPHYSICS AND
PLANETARY PHYSICS
LA JOLLA LABORATORIES
LA JOLLA, CALIFORNIA

18 May 1967

TO: All Agencies on Distribution List

RE: Technical Report
Contract AF49(638)-1388
Grant AFOSR-1007-66

Gentlemen:

Enclosed you will find an errata to the above referenced reports.

Please accept our apology. The order of credit was an error in copy work and not Dr. Bradner's original draft.

Very truly yours,

Ruthellyn Uncapher
Ruthellyn Uncapher (Mrs.)
Secretary to Dr. H. Bradner

and
enclosures
cc:

Mr. Gary V. Latham
Lamont Geological Observatory of Columbia University
Palisades, New York 10964

The ocean-bottom coherence in the microseism peak implies that water motion is, however, not responsible for the large observed ocean-bottom peak power. The ocean/land ratio is usually taken to indicate poor energy transport toward the continents, though Latham and Sutton have recently argued that the elastic characteristics of the bottom can influence the records enough to account for the ratio (ref. 2). The following argument lends qualitative support to their view in one case at least. Fig. 4 shows land and sea spectra from records about four hours apart during uniform quiet weather at an isolated mid-Pacific island. The ocean measurements were made in 1500 ft. water depth, ten miles from Swain's Island which lies about 150 miles from the nearest significant land mass, Samoa. Swain's is a one mile diameter coral island with underwater contours and a scaled profile of the island. Even if we assume seismic wave velocity as small as 2 km/sec., then one wavelength at 1/4 cps is the size of the figure. The island base and height are small compared with the wavelength, and hence would be expected to have little effect on the seismic energy transport for frequencies below 1/4 cps. The spectrum of Fig. 4 shows that the peak land power was smaller than the peak ocean-bottom power by a factor of 100, even though the land seismometer was simply buried under a foot of loose coral in a cocoanut grove a hundred yards from the edge of the reef. The transmission characteristics from ocean to land should not account for the large power difference in this example. The elastic characteristics of the environments, however, could be significant.

2.

MIDWATER INSTRUMENTS

We have reported that ocean-bottom spectra frequently show a

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